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Grid Integration of Aggressive Renewable Energy Targets in India

Assessment of Long Term Investment Pathways using Grid Planning and Dispatch Analysis

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Nikit Abhyankar, Amol Phadke

1 Introduction

Recently, several planning and policy initiatives have been proposed in India for large-scale deployment of renewable energy (RE). Ahead of the Paris Conference of Parties (COP) in November-December 2015, India announced increasing the installed capacity of solar power projects from about 3 GW in 2014 to 100GW by 2022 and increasing the wind power capacity from nearly 20GW to 60GW in the same timeframe. The government and the private sector have already shown significant commitment to achieve these targets. For example, the government has approved setting up over 20GW of solar capacity in 25 "Ultra-Mega Solar Parks" spread across the country and has also offered a financial support of nearly US$650 million.

Given the proposed addition to the renewable capacity, there is significant discussion on the policy, regulatory and commercial strategies to integrate RE in the Indian power system. Large scale RE grid integration has been analyzed widely in the US and European context (see for example: (Palchak and Denholm 2014; Cochran et al. 2015; Milligan et al. 2013; A. D. Mills and Wiser 2013; Andrew D. Mills 2014; Orans et al. 2013) etc.). However, there is limited literature in the Indian context. Few studies have assessed the variability and capacity value of renewable energy in India (Hummon et al. 2014; Phadke, Abhyankar, and Rao 2014; George and Banerjee 2009; Chattopadhyay and Chattopadhyay 2012); but they do not deal with the grid integration issues in detail.

Very few studies have conducted comprehensive grid dispatch modelling and investment planning analysis. The Report on Green Energy Corridors analyses the flexibility of the Indian power system for integrating a total of 72,400 megawatts (MW) of RE by 2022 (POWERGRID 2012). However, the analysis in that report is limited to the typical day per month and therefore, does not capture the entire range of annual hourly load and renewable generation variability. The Asian Development Bank, as a part of their technical assistance to the government of India, conducted a comprehensive cost-benefit analysis study of six major electric power interconnection projects in South Asia (ADB 2013). However, their analysis was primarily focused on assessing the cross-border energy trade and transmission investments using power flow modelling (to assess the actual power transfer capabilities). (Shakti 2013) analyzes the economic impact of integrating renewable energy in the Indian grid using grid dispatch modelling. That study, however, does not consider very aggressive RE penetration and there is no significant variation in the RE penetration numbers across multiple scenarios e.g. in their most aggressive scenario they assume an RE penetration of 25% by energy by 2031; while the baseline penetration is assumed to be 16% by energy. The government of India recently released a few reports that broadly assess the strategies to integrate RE most notably by CEA and NITI Aayog. India's Central Electricity Authority published a document in 2013 that laid out the key issues in RE grid integration and assessed the strategic solutions (CEA 2013a). NITI Aayog released a roadmap for accelerating the deployment of renewable energy in India that highlights the key issues facing RE deployment in India ranging from financing costs to integration risks (NITI 2015). These analyses, however, do not assess the technical feasibility or quantify the economic impacts of RE integration.

The objective of this paper is to assess the technical feasibility of integrating aggressive renewable energy targets into the electricity grid in India and broadly identify the long-run investment pathways for RE grid integration in India such as expansion of the flexible electricity generation technologies like gas turbines etc. We conduct the analysis by simulating the economic dispatch and operation of the power system for the financial year 2047 using PLEXOS for a variety of renewable energy penetration scenarios defined in NITI Aayog's India Energy Security Scenarios (IESS) model. National Institution for Transforming India (NITI Aayog), Government of India's apex planning agency, recently conducted a modelling exercise to assess the impact of the key fuel and energy policy choices on India's energy security in the long run (2047). Based on the UK Department of Energy and Climate Change's 2050 Calculator, NITI Aayog built a comprehensive energy scenario-building tool, IESS, through a multi-stakeholder process over two years. It explores a range of potential future energy scenarios for India leading up to 2047, for diverse energy supply sectors such as solar, wind, biofuels, oil, gas, coal, and nuclear, and energy demand sectors such as transport, industry, agriculture, cooking, and lighting and appliances. The model also allows users to interactively change energy choices, and explore a range of outcomes for the country such as carbon dioxide emissions, import dependence of fuels, land-use, issues in the RE grid integration etc.

We believe that our results would inform the long run investment and operational solutions to integrate large scale RE in India in the long run. Creating an appropriate policy and regulatory framework for such solutions would be crucial for achieving high penetration of RE resources. Moreover, our results would provide a preliminary estimate of the incremental cost integrating the RE into the grid. Since such costs would be borne by certain players (primarily utilities) in the power sector, quantifying them is essential for designing potential commercial arrangements to address the adverse impact on any particular stakeholder.

The remainder of the paper is organized as follows. Section 3 gives a broad overview of the Indian power sector followed by section 3 that describes our methodology, data, and assumptions. In section 4, we present key results of the analysis. In section 5, we conclude the paper by identifying the key medium to long term investment pathways for enhancing the system flexibility in India for integrating the aggressive RE targets and discuss the opportunities for future work. Annexure provides average hourly dispatch for each season for multiple scenarios considered in the paper.

2 Overview of the Indian Power Sector

With peak electricity demand of 150 GW and the total installed capacity of about 230GW, India has one of the largest electricity transmission and distribution systems in the world (CEA 2015c). State government companies own more than half of existing installed generation capacity, and central (federal) government corporations own a third. The remainder is owned by the private sector. By contrast, more than 87% of the distribution sector (by sales) is owned by state-government utilities, and the rest is owned by private and municipal utilities (CEA 2008).

2.1 Renewable Energy

Several recent studies have shown immense solar and wind energy potential in India. For example, at 20% capacity factor and above, total wind energy potential in India is in excess of 3000 GW (Phadke, Bharvirkar et al. 2012). Similarly, total solar PV potential in India is as high as 11,000 GW (Ramachandra, Jain et al. 2011; Sukhatme 2011; Deshmukh and Phadke 2012).

Almost all key states in India have enforced Renewable Portfolio Standards (RPS) that mandate the load serving entities and captive users to purchase a fraction of their annual electricity requirements from renewable energy sources. In addition to RPS, renewable energy sources are offered feed-in tariffs. The following table shows the RPS mandates in the key states.

State	RPS Target (2015)
Maharashtra	9%
Gujarat	8% (2015) 10% (2017)
Tamil Nadu	9% (non-solar) 0.5% (solar)
Karnataka	7-10% (non-solar) 0.25% (solar)
Rajasthan	9% (2015) 11.4% (2017)
Andhra Pradesh	4.75% (non-solar) 0.25% (solar)
Madhya Pradesh	6% (non-solar) 1% (solar)

Data source: (MNRE 2015)

In addition, the central government offers significant financial incentives such as generation based incentive or accelerated depreciation for aggressive deployment of renewable sources. As a result, the RE capacity has increased by

2.2 Electricity Grid and Transmission

The Indian power grid is an interconnected 50Hz network. Currently, there are five regional grids (all synchronized) – north, south, west, east and north-east; each region is made up of 5-7 states. In most cases, each state is an independent balancing area. The state grids are operated by the State Load Dispatch Centers while the interstate transactions within a region (interstate generating stations and the transmission system) are operated by the Regional Load Dispatch Centers. The inter-regional transmission system is operated by the National Load Dispatch Center. The wholesale electricity market in India is in nascent stages. India does operate a day-ahead electricity market with the gate closure time of one hour i.e. day-ahead schedules could be updated up to an hour in advance. However, only about 3% of the total annual energy generation is traded on the day ahead market while 95% is based on long term PPAs and short-term bilateral contracts (IEX 2015). Although there is no formal real time market in India, the deviation settlement mechanism acts as the de-facto real time market where the real time price is dependent on the system frequency. Such real time deviations of each utility relative to the day-ahead schedule are capped at 150 MW or 12% of the schedule, whichever is lower. In 2016, India has also created a framework for ancillary services market.

The following tables show the current installed capacity, peak demand, and energy requirement in India in each region by technology.

Table 1: Installed Capacity (MW) in India by region (March 2015)

	North	West	South	East	North-East	All-India
Coal	39,431	66,220	30,343	28,583	60	164,636
Gas	5,331	10,915	4,963	190	1,663	23,062
Diesel	13	17	939	17	143	1,130
Nuclear	1,620	1,840	2,320	-	-	5,780
Hydro	17,067	7,448	11,398	4,113	1,242	41,267
Wind	3,053	8,517	10,891	4	-	22,465
Solar	962	1,638	416	62	-	3,078
Small Hydro	1,331	490	1,670	238	262	3,991
Biomass + Cogeneration	1,094	1,275	1,555	89	-	4,014
Total	**69,902**	**98,360**	**64,495**	**33,296**	**3,370**	**269,422**

Data source: (CEA 2015b)

Power shortage is a chronic problem in the Indian power sector. However, with significant capacity additions in the recent years, the power shortage has reduced in recent years. In the financial year 2014-15 (April 2014 through March 2015), India faced nearly 5% peak shortage and about 3.5% of energy shortage.

Table 2: Peak (MW) and Energy (GWh) Demand and Availability by Region (for FY 2014-15)

Region	**Energy (GWh)**		**Peak (MW)**	
	Demand	**Availability**	**Demand**	**Availability**
North	332,453	311,589	51,977	47,642
West	317,367	314,923	44,166	43,145
South	285,797	274,136	39,094	37,047
East	119,082	117,155	17,040	16,932
North-East	14,224	12,982	2,528	2,202
All-India	**1,068,923**	**1,030,785**	**148,166**	**141,160**

Data Source: (CEA 2015a)

Since all states and regions are synchronized since 2014, the transmission constraints across state and region boundaries have started relieving significantly. The following table shows the existing transmission capacity in June 2015 between the regions in India.

Table 3: Existing inter-regional Transmission Capacity in India (June 2015)

Corridor	Transmission Capacity (MW) (June 2015)
East-North	15830
East-West	10690
East-South	3630
East-North-East	2860
West-North	8720
West-South	5720

Source: (MOP 2015)

Note that the numbers shown in this table are the total transmission capacity. The actual concurrent power transfer capability (considering congestion, reverse flows, and other technical constraints) may be much lower than this.

Over the next 30-40 years, Indian power sector is poised to expand significantly. For example, the peak power demand is expected to nearly double to about 287GW by 2022, more than triple to nearly 500 GW by 2030, and more than quadruple to nearly 800 GW by 2047 (CEA 2013c; NITI Aayog 2015).

3 Methodology and Assumptions

We model the Indian electricity grid as a single node system. An implicit assumption is that there are no transmission constraints in the country by 2047. We project the hourly national demand in 2047 using the total electricity demand projections in the IESS and the hourly demand patterns over the financial years 2010 through 2013 adjusting for rapid urbanization and changing appliance use patterns. We then created a wide range of scenarios for renewable energy penetration using the RE installed capacity levels in IESS. We use actual hourly generation and weather data to project the hourly wind and solar generation for 2047. We develop assumptions and make several simplifications regarding operational performance of generation technologies.

We use PLEXOS to simulate economic dispatch for the financial year 2047 subject to a range of operational constraints.[1]

Based on such simulations, we assess how the grid may be dispatched in 2047, whether the renewable energy could be reliably integrated, whether any RE curtailment is necessary, and whether the flexible capacity (such as gas, hydro etc) defined in the IESS scenarios is enough for reliable RE grid integration; we use PLEXOS's capacity expansion module to determine the additional flexible capacity that would be needed. We assume that such additional flexible capacity (if required) to be gas based open cycle turbines

[1] PLEXOS is a production cost model that optimizes the investments and economic dispatch of power plants considering unit commitment etc. used widely by the utilities and system operators/planners across the world. We are thankful to energy exemplar inc. for providing PLEXOS license to us at research institution rate.

– however, that could also be viewed as any other fast ramping technology. The methodology is summarized Figure 1 and the following section describes it in detail.

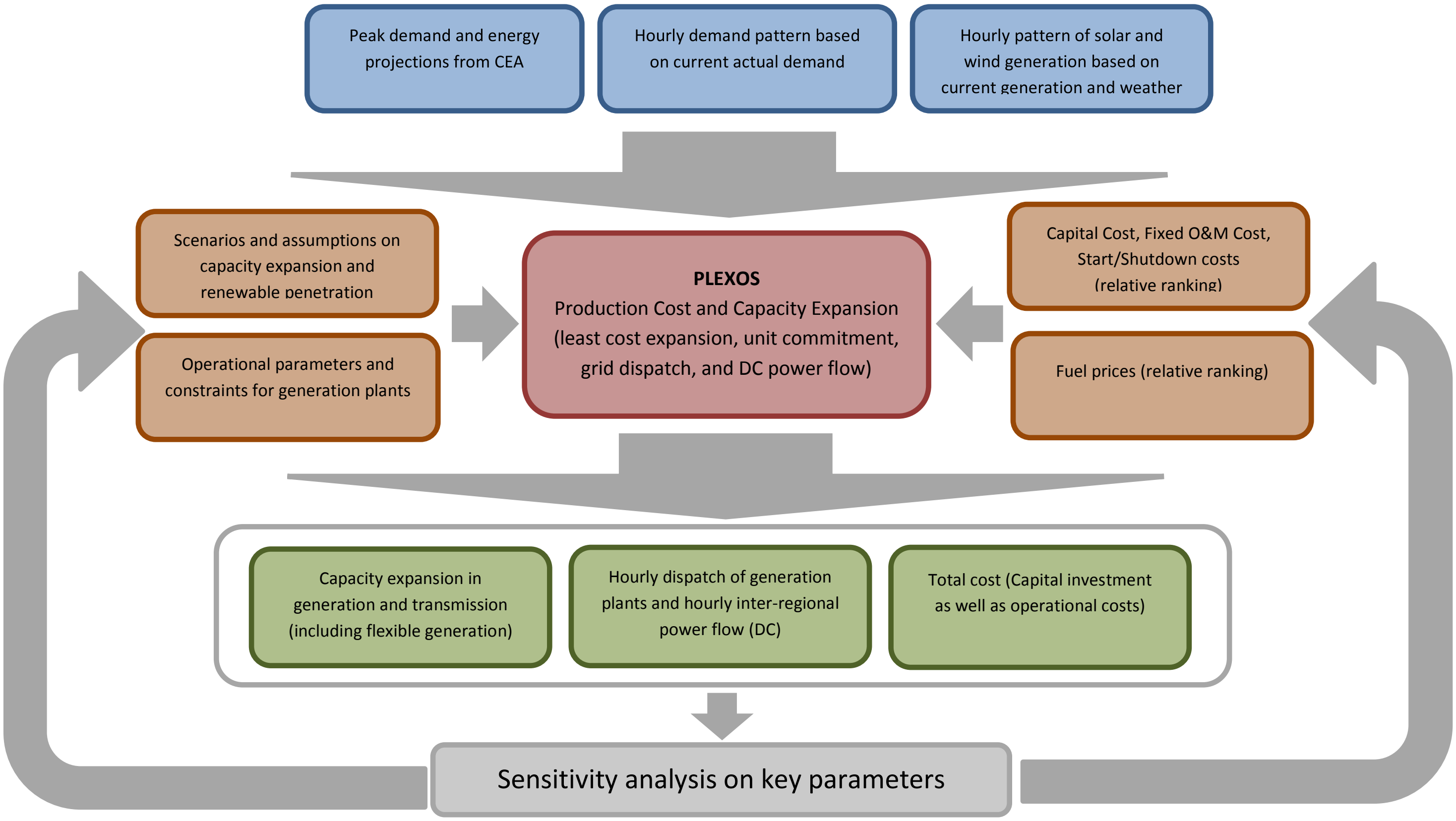


Figure 1: Summary of the Methodology

3.1 Scenarios for RE Penetration

We conducted this exercise for a range of energy scenarios identified in the Indian Energy Security Scenarios (IESS) model (v2.0) for a variety of renewable energy supply levels and electricity demand levels. Each scenario we have selected a unique set of conventional capacity, renewable penetration, and demand level. IESS creates four levels for each supply side resource as well as all demand side sectors – each level has different assumptions on the growth of electricity consumption in the country and efficiency of electricity utilization. The following table lists all the scenarios we have assessed in this paper. The table also shows the shares of RE and other non-fossil sources such as hydro, nuclear etc. in total electricity generation in 2047 and demand level. Note that in some scenarios, the total share of the non-fossil electricity (by energy) is as high as 80% by 2047.

Table 4: RE penetration, share of non-fossil based generation, and demand level in 2047 for each IESS scenario considered in this paper

Scenario name	RE Share (by Energy)	Share of Other non-fossil (by energy)	Total non-fossil share in 2047 (by energy)	Demand Level
Least Effort Pathway	6%	4%	10%	**1**
Determined Effort Pathway	22%	8%	30%	2
Aggressive Effort Pathway	38%	14%	52%	3
Heroic Effort Pathway	58%	23%	82%	4
Renewable and Clean Energy Pathway	48%	16%	64%	2
Minimum Emissions Pathway	58%	23%	81%	4
Maximum Energy Security Pathway	55%	15%	70%	4
RE 13%, Demand Level 2	13%	6%	19%	2
RE 16%, Demand Level 1	16%	1%	17%	1
RE 16%, Demand Level 4	16%	7%	23%	4
RE 22%, Demand Level 3	22%	8%	30%	3
RE 23%, Demand Level 2	23%	5%	28%	2
RE 27%, Demand Level 1	27%	1%	28%	1
RE 32%, Demand Level 2	32%	5%	37%	2
RE 33%, Demand Level 3	33%	6%	39%	3
RE 33%, Demand Level 4	33%	5%	38%	4
RE 34%, Demand Level 1	34%	3%	37%	1
RE 39%, Demand Level 3	39%	6%	45%	3
RE 42%, Demand Level 1	42%	3%	45%	1
RE 42%, Demand Level 4	42%	6%	48%	4
RE 44%, Demand Level 2	44%	2%	46%	2
RE 46%, Demand Level 3	46%	6%	52%	3
RE 51%, Demand Level 1	51%	4%	55%	1
RE 54%, Demand Level 2	54%	2%	56%	2
RE 54%, Demand Level 3	54%	10%	64%	3
RE 54%, Demand Level 4	54%	9%	63%	4
RE 62%, Demand Level 4	62%	8%	70%	4

3.2 Hourly demand forecast

IESS creates four levels of demand – each with different assumptions on the growth of electricity consumption in the country and efficiency of electricity utilization. Using these demand levels, we simulated an hourly demand curve for the financial year 2047 based on the historical hourly demand patterns in the country, load growth, and projected urbanization.

One of the key problems in projecting the future hourly pattern based on historical trends was accounting for the load curtailment (which was as high as 6% by energy in 2013). To address that, we used a mixed approach. We used the current restricted load data for each region to assess the seasonal load pattern in a region; and used hourly load data of the key load centers that do not experience load shedding (such as Delhi, Chandigarh, Gujarat, Mumbai, Pondicherry etc.) and the load centers that have the load shedding data available (such as Maharashtra, Tamil Nadu etc.) to assess the diurnal demand pattern.

The following table shows the annual load factors (ratio of the annual average demand to peak demand) in key cities that do not face significant power cuts as well as for the entire country.

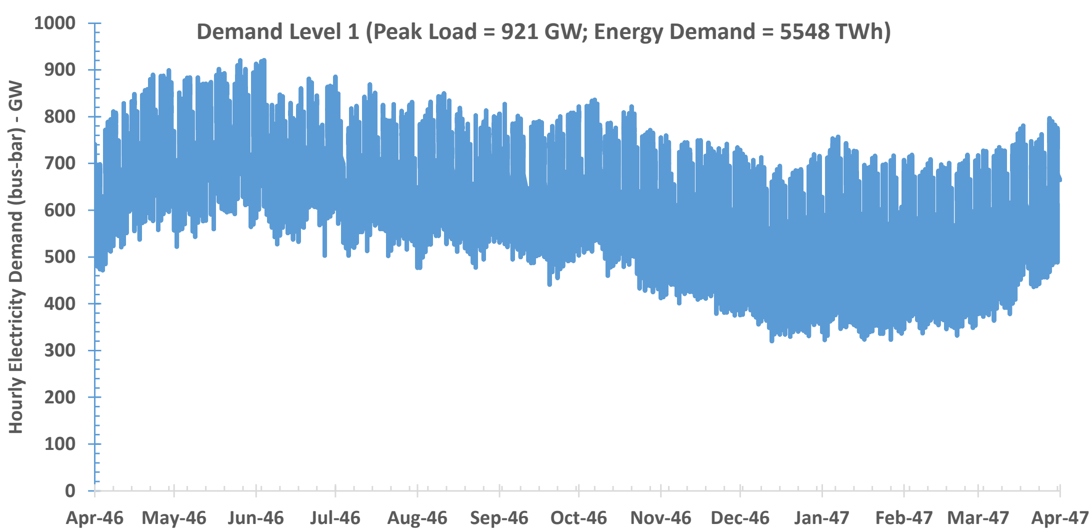
Table 5: Annual load factors in key cities and regions (financial years 2000 through 2015)

	2000	2010	2012	2013	2014	2015
Chandigarh		63%	68%	55%	52%	50%
Delhi		65%	61%	52%	54%	56%
Pondicherry		91%	76%	82%	80%	78%
Mumbai		69%	68%	65%	#N/A	#N/A
All India	***80%***	***87%***	***84%***	***84%***	***84%***	***83%***

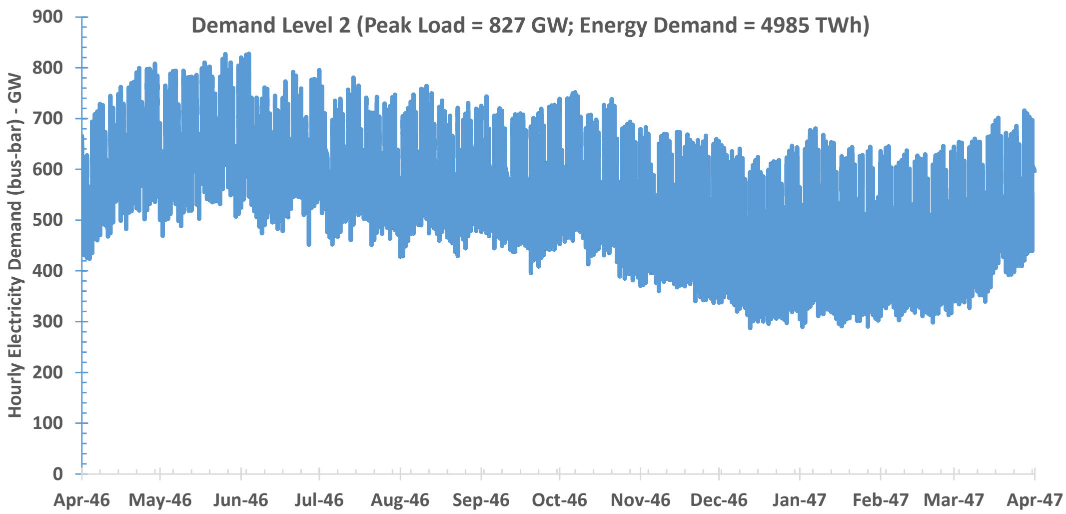
Data Sources: (CEA 2015a; CEA 2015c; CEA 2012; CEA 2013b; CEA 2009)

Across all cities, load factors have been reducing in the recent years; this implies that the demand is becoming peakier in nature. This may be happening due to two reasons viz. (a) availability of power has been increasing resulting in reduced shortages, and (b) due to rapid urbanization, electricity usage pattern and appliance ownership have changed significantly. To account for the growing urbanization in the country, load shapes of the urban load centers (such as Delhi, Mumbai, Pondicherry etc.) are given an additional 50% weight relative to the state level load curves in each region. This would make the resultant 2047 hourly load curve significantly peakier than the current (2015) one. Finally, the national load curve is uniformly adjusted so the total peak and energy demand matches IESS's 2047 projections. We understand that demand forecast and load shape assessment is an area where future work is needed using a combination of bottom up and top down approaches.

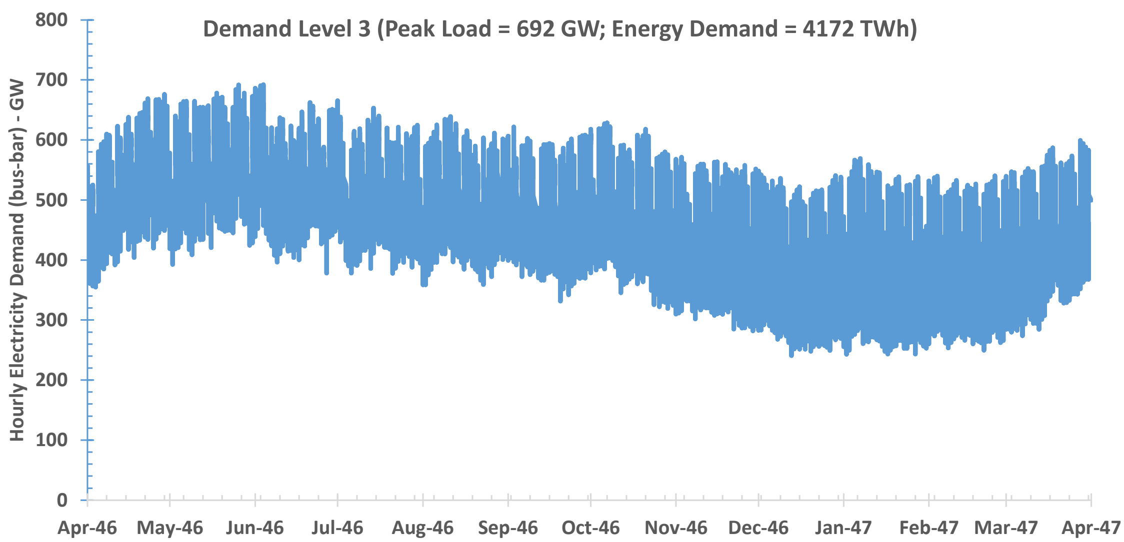
The following charts show the projected hourly load curves for India in financial year 2047 for each demand level (1 through 4).



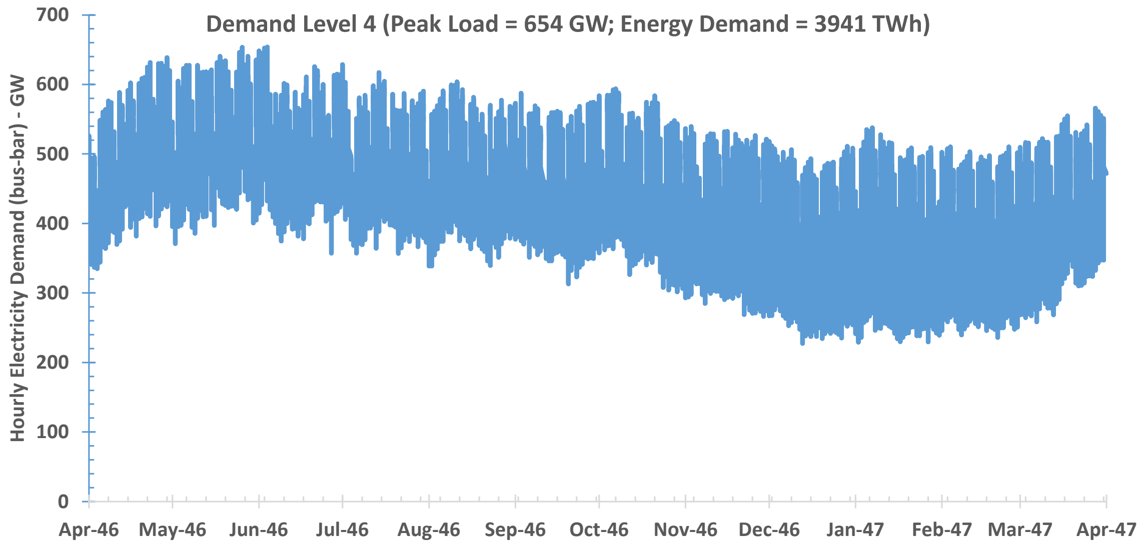
For demand level 2, the electricity demand reduces by nearly 10% because of the undertaken energy efficiency measures, as can be seen from the following chart.



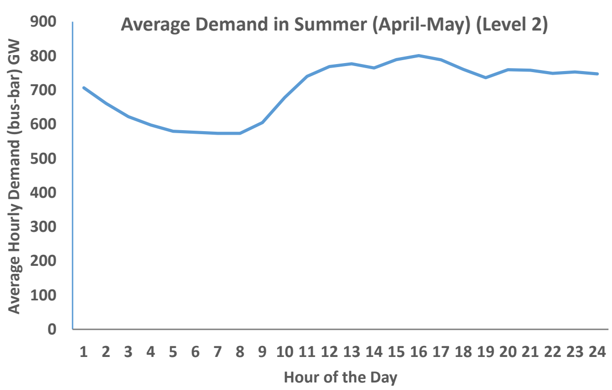
In level 3, the demand reduces further by about 15%.

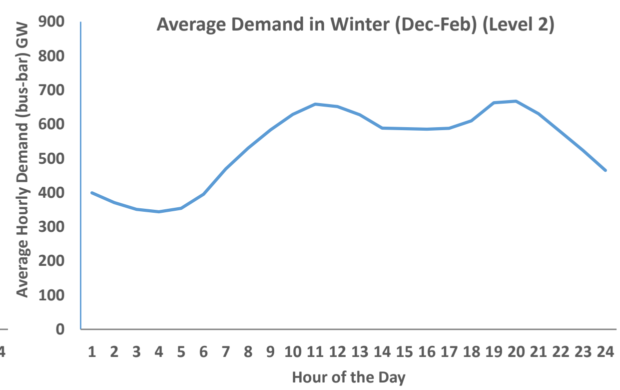


The demand reduces further by about 5% in level 4.



In all demand levels, the electricity demand peaks in the summer (April through June) mainly due to space cooling load. It drops somewhat in the monsoon (July onwards) while the demand is lowest in the winter (November – February). Because of the space-cooling load, the demand in the summer is mostly afternoon peaking. Winter demand, on the other hand has two distinct peaks – one in the morning (due to water heating) and one in the evening (due to lighting). The following chart shows the average daily load curve for summer (April-May) and winter (December through February) in FY 2046-47 for demand level 1.





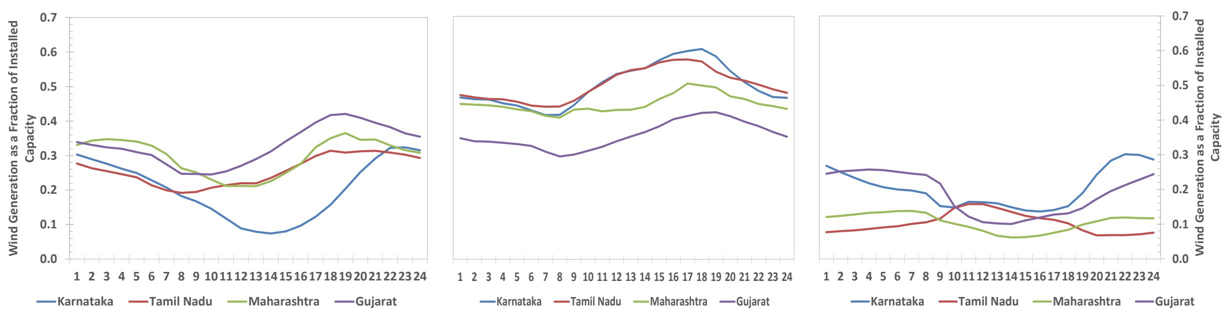
Electricity demands for other demand levels would be lower, but will follow a very similar seasonal and diurnal pattern.

3.3 Hourly solar and wind generation forecast

3.3.1 Wind Energy Generation Profiles

India's current wind installed capacity is more than 21GW and has been growing consistently over the last 10 years or so. Indian wind energy generation is highly seasonal and peaks during monsoon. For FY 2022, Hourly profiles of wind energy generation have been forecasted using the actual historical generation data for the financial years 2010 through 2013 from the states of Tamil Nadu, Karnataka, Maharashtra, and Gujarat. These states together cover over 80% of the existing wind installed capacity and over 75% of the total wind potential in India (CWET 2014; Phadke 2012). Hourly wind generation data for Maharashtra and Tamil Nadu was sourced from the websites of their state load dispatch centers; for other states, the data was made available by POSOCO. We understand that the reported wind generation does not take into account the curtailment. Therefore, actual data may not represent the true profiles of wind generation. Unfortunately, the data on exact amount and timing of curtailment is not available. Secondly, industry experts suggest that wind energy curtailment was quite limited until the financial year 2012-2013 (Phadke, Abhyankar, and Rao 2014).

The following chart shows the seasonal averages of the wind energy generation (as a share of the installed capacity) in the key states mentioned above.



Summer (April-May) Monsoon (June-September) Winter (Dec-Feb)

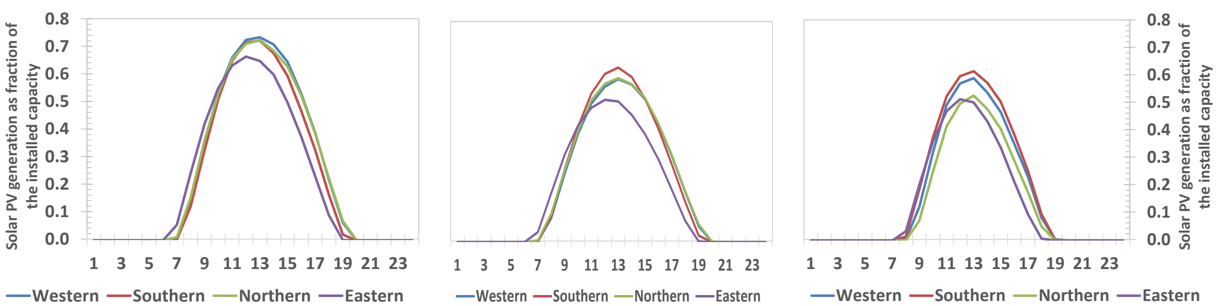
Figure 2: Average daily wind generation curve (of existing capacity) in key states for key states

It can be seen that there is significant seasonal variation in wind generation in all states. Wind generation peaks in monsoon (June through September) and drops significantly in the winter. But the diurnal pattern of wind generation in a season is very similar across all states. In Monsoon and Summer, the wind generation peaks late afternoon or early evening which matches with the overall demand patterns in these seasons.

For future wind capacity addition, we used the wind energy potential numbers in each state from our previous study assessing the wind energy potential in India (Phadke 2012). For estimating the hourly wind generation profile for a future year (2047, in this case), the approach in other studies has been to use time-series data from meso-scale models. But in this study, we are scaling the actual generation data for the current year, which assumes that the additional capacity will be installed in the same regions, and hence will have the same profiles. However, in reality, capacity addition will occur in different areas, which is likely to reduce the overall variability of the wind generation at the regional level due to geographic diversity of the wind installations. However, given that verified hourly wind resource data was not available in the public domain, we could not use wind resource data from undeveloped sites. Thus, wind variability in this analysis would be high and the capacity value conservative; and could be seen as the worst-case scenario of the future wind capacity addition. More detailed analysis (for example using time-series meso-scale resource data) is needed to improve the profiles of wind generation used in this analysis.

3.3.2 Solar Energy Generation Profiles

Unlike wind, total grid connected solar PV capacity in India is only 3 GW albeit it is increasing rapidly given the dropping costs and favorable regulatory and policy environments. The largest capacity of 1.5 GW is operational in the state of Gujarat. But several studies have shown practically infinite solar energy potential in India. For estimating the hourly generation profile, we chose 100 sites spread over all 5 regions with best quality solar resource (measured in Direct Normal Irradiance and Global Horizontal Irradiance kWh/m2) using the national solar energy dataset for India developed by the National Renewable Energy Laboratory that contains hourly irradiance data for every 5kmx5km grid in India. The solar irradiance data was then fed into the System Advisor Model (SAM) also developed by the National Renewable Energy Laboratory to get the solar PV output at the chosen 100 sites. The hourly PV output profiles of the sites in each region was averaged to arrive at the regional solar PV generation profile. The average generation profiles for each season are shown in the charts below.



Summer (April-May) Monsoon(June-September) Winter (Dec-Feb)

Figure 3: Average daily solar generation curves for each region

As can be seen from the charts that the solar resource peaks in the summer and drops in winter. However, the seasonal variation is not as dramatic as that in case of wind. It may appear that there is not much difference in the average resource quality of the western, northern and southern regions; however, resource quality would vary significantly at the individual site level. Most of India's best quality solar resource is concentrated in the western and the northern region. As explained in the previous section on wind energy, we assume that the future solar capacity is added at the sites selected for estimating the hourly generation profile. Therefore, it will not fully capture the benefits of geographic diversity and may overestimate the variability to some extent.

3.4 Operational Parameters of Generators

Table A.1 in Annexure 1 summarizes our assumptions on the operational characteristics (unit size, heat rates, ramp rates, minimum stable level etc) of the power plants. The values have been estimated using the actual plant level hourly dispatch data, actual outage and other performance data, regulatory orders on heat rates and costs, other relevant literature, and conversations with the system operators in India about actual practices. Currently, the combined cycle (gas) plants in India are not operated in the open cycle mode (gas turbine only; no waste heat recovery). However, by 2047, we assume that the gas turbines in the combined cycle plants could be operated independently in open cycle mode, which enhances the system flexibility considerably.

3.5 Hydro capacity and energy model

Hydro capacity is modeled using a fixed monthly energy budget. Based on the historical dispatch and minimum flow and spill constraints we estimated the capacity factors of the hydro power plants for every month. Subject to such monthly capacity factor constraints, reservoir based hydro power plants are assumed to be optimally dispatched. The following table shows the monthly capacity factors for hydro plants in each region:

Table 6: Monthly Capacity Factors of Hydroelectric Projects for Each Region

	East	North-East	West	South	North
January	18%	25%	30%	28%	24%
February	18%	23%	27%	32%	29%
March	19%	22%	26%	40%	36%
April	25%	34%	26%	31%	40%
May	18%	49%	26%	27%	62%
June	27%	61%	23%	27%	64%
July	28%	80%	27%	31%	67%
August	27%	83%	47%	37%	67%
September	32%	67%	49%	54%	71%
October	26%	60%	38%	39%	40%
November	16%	40%	26%	29%	29%
December	8%	26%	21%	24%	26%
Annual Average	***22%***	***47%***	***30%***	***33%***	***46%***

Hydro capacity factors depend on a variety of factors including high recharge season (such as summer or monsoon), irrigation and minimum flow requirements etc.

More than 50% of India's current hydro capacity is run of the river; output of the run-of-the-river plants is assumed to be flat subject to the monthly capacity factor constraint. India has limited pumped storage capacity; they are modeled using a weekly energy balance i.e. the head and tail storage ponds return to their initial volumes at the end of each week. We ran a sensitivity case with daily energy balance but given the small pumped storage capacity, it does not make a large difference to the overall results.

3.6 Costs

Given the long-term horizon of the analysis, any projection of the costs especially when projected using the last few year's data would not be accurate. Since this exercise is not a capacity planning exercise, we take installed capacity of each technology as given in the IESS pathways except in case of the flexible generation.

We use PLEXOS's capacity expansion module to assess the flexible capacity requirement for balancing. We use nominal (weighted average of the entire conventional generation fleet) capital cost of $800/kW and fixed O&M cost of $35/kW/year for that. Since this is the only capacity that gets added in the capacity expansion module, choice of the precise value of the fixed cost would have no effect on the capacity addition as long as the capital cost is positive.

The relative marginal costs of generation (i.e. variable fuel costs) of different technologies and their trends, however, need to be specified in order for the model to make dispatch decisions. The following table shows our assumptions on the fuel price, heat rates, and the marginal generation cost for the fossil fuel and biomass based power plants. Note that we mentioned earlier, the flexible generation capacity for grid balancing is assumed to be gas based. All other non-fossil technologies (hydro, renewable, and nuclear) are assumed to have zero marginal generation costs (i.e. variable cost). Also, we assume that there are no constraints on fuel availability by 2047. We have taken the current year (2015) fossil fuel (coal and gas) and biomass prices and have assumed that they remain constant in real terms up to 2047. As long as these costs do not change the relative ranking of the marginal generation costs, their precise value would not change the dispatch decisions significantly. For example, as long as the marginal cost of generation from coal plants is lower than that from gas based plants, coal plants would always have a priority in dispatch except in periods of fast ramping that coal cannot provide.

Domestic coal price data have been taken from Coal India Limited's annual report as the average price of coal sold by CIL in that year (CIL 2011; CIL 2015).[2] Imported coal prices have been taken from the BP Statistical Review (Asian marker price) (BP 2015). Domestic natural gas price has been taken from the Ministry of Petroleum and Natural Gas's orders. Imported LNG price has been taken from the media reports on the international LNG market.

Table 7: Fuel Price Assumptions

Fuel	Fuel Price in 2015 (FOB)
Domestic Coal (Rs/Ton)	1,948
Imported Coal ($/Ton)	77.89
Domestic Gas ($/mmbtu)	4.66
LNG ($/mmbtu)	11
High Speed Diesel (Rs/lit)	50
Biomass (Rs/Ton)	2,000

Data Sources: *Ibid*

Note that these are the FOB (free on board) prices and do not include the fuel transportation and LNG regasification etc. costs. We take the national weighted average of the fuel transportation costs based on (Phadke, Abhyankar and Deshmukh 2016), which is given in the following table:

[2] Coal India Limited controls more than 80% of India's total coal production and about 80% of its coal is sold to the power sector.

Table 8: National Weighted Average Fuel Transportation Costs

	National Weighted Average Fuel Transportation Cost	
	Domestic transportation	International transportation
Domestic Coal (Rs/Ton)	1,500	-
Imported Coal ($/Ton)	-	30
Domestic Gas ($/MMBTU)	1.5	-
Imported LNG ($/MMBTU)	-	1.5 (including Regasification)
Biomass (Rs/Ton)	500	-

Data Source: *Ibid*

3.7 Transmission

Recently southern regional grid in India was integrated with the northern regional grid. Additionally, there have been significant transmission investments planned in the near future. Going forward, we have assumed no constraints on transmission primarily to assess the transmission transfer capability requirements between the regions in future.

Note that this study tests only the preliminary feasibility of grid dispatch and broadly identifies storage and balancing needs. A comprehensive study, which looks at transmission constraints and investments, specific storage technologies, and flexible capacity needs, would be required to answer more specific questions on the feasibility of grid dispatch and grid integration strategy of renewables.

4 Results

In this section, we present the key results of our analysis. In order to develop an intuitive understanding of the results and keep them tractable, we are only going to present the results for an average day in each season. Detailed hourly results can be made available upon contacting the authors.

Based on the simulation results, we find that all the pathways are technically feasible and the electric grid can be reliably dispatched with support from additional grid balancing / flexible sources like open cycle gas turbines, storage (batteries, pumped hydro etc.) or smart grid /demand response etc.

4.1 How much flexible capacity is needed for renewable energy grid integration

In general, when the grid has very high RE penetration, the system would need significant capacity of flexible resources in order to integrate the renewable energy projects into the grid reliably. The key services provided by the grid balancing sources are primarily: (a) fast ramping support to manage the short-term (minute to minute) variability in the renewable energy generation, (b) ramping support (ramp-up and ramp-down) particularly during morning and evening peak hours, and (c) energy support during winter evening peak periods, as wind and solar outputs drop. If the flexible capacity includes storage resources, then it should also be able to minimize the renewable energy curtailment by drawing excess energy from the grid.

The following tables show the total installed capacities in 2047 for each scenario we have considered in the paper. As mentioned earlier, we take the installed capacities for all generation technologies except grid balancing requirement as given from the IESS model. PLEXOS's capacity expansion module then adds the optimal grid balancing capacity (assumed to be gas open cycle turbine), if required, in order to meet the demand and the ramps reliably.

Table 9: Installed Capacity (GW) by technology in 2047 for IESS pathways

	Least Effort	Determined Effort	Aggressive Effort	Heroic Effort	Renewable and Clean Energy	Pathway X	Min Emissions	Max Energy Security
Coal	261	368	539	681	413	494	261	368
Gas_CCGT	37	50	83	132	83	83	37	132
Nuclear	11	26	45	78	78	26	78	45
Hydro	49	75	105	150	105	75	150	105
Biomass+Cogen	5	11	23	20	23	11	20	20
Hydro_Small	9	15	20	30	30	20	30	20
Wind	71	222	332	551	551	290	472	472
Solar	56	243	449	930	833	405	930	833
Electricity Imports	504	135	0	0	0	0	0	0
Waste to Electricity	0	4	6	6	6	4	6	6
Storage	5	25	33	43	43	33	43	43
Total Installed Capacity (GW)	**1008**	**1173**	**1635**	**2621**	**2164**	**1441**	**2026**	**2043**
Peak Load (GW)	**921**	**827**	**692**	**654**	**827**	**692**	**654**	**654**

It can be seen that in several of the selected pathways, the generation capacity is significantly higher than the peak demand for that pathway – except for least effort and determined effort pathways. For these two pathways, the planned generation capacity is not able to meet the electricity demand fully. Therefore, significant additional resources would be necessary to avoid electricity shortages and not necessarily to integrate renewable energy. In all other pathways, there is significant over-capacity in generation with conventional and dispatchable generation covering nearly 80-90% of peak demand. Therefore, there is no need for additional flexible resources for grid balancing. The following table shows the additional grid balancing capacity requirement and its capacity factor for each pathway.

Table 10: Capacity factors of the additional grid balancing capacity for each IESS pathway

Pathway	Additional Grid Balancing Support (GW) (storage, peaking plants etc)	Capacity Factor
Least Effort	335	89%
Determined Effort	82	84%
Aggressive Effort	0	0%
Heroic Effort	0	0%
Renewable and Clean Energy	0	0%
Pathway X	0	0%
Min Emissions	0	0%

Max Energy Security	0	0%

In the Least Effort and the Determined Effort pathways, the grid balancing resources are used not only as the sources for flexibility but also as energy resources, which is evident from their high capacity factors. In all other pathways, although the renewable energy penetration is very high, the conventional capacity already available to balance such high RE penetration is also high and therefore, no additional flexible resources are required.

Table 11: Installed Capacity (GW) by technology in 2047 for IESS scenarios

	RE 13%,Demand2 FY 2047	RE 16%,Demand1 FY 2047	RE 16%,Demand4 FY 2047	RE 22%,Demand3 FY 2047	RE 23%,Demand2 FY 2047	RE 27%,Demand1 FY 2047	RE 32%,Demand2 FY 2047	RE 33%,Demand3 FY 2047	RE 33%,Demand4 FY 2047	RE 34%,Demand1 FY 2047
Coal	586	897	374	389	506	735	438	364	281	688
Gas_CCGT	50	37	50	50	50	37	50	50	50	37
Nuclear	26	11	26	26	26	11	26	26	26	11
Hydro	75	49	75	75	75	49	75	75	75	49
Biomass+Cogen	8	3	8	8	8	3	8	8	8	3
Hydro_Small	15	15	9	9	15	20	15	15	15	20
Wind	64	215	64	199	215	325	282	215	215	544
Solar	207	243	169	169	243	449	405	405	243	449
Electricity Imports	35	35	70	35	35	58	35	35	70	35
Waste to Electricity	4	4	4	4	4	6	4	4	4	4
Additional Grid Balancing Support	24	75	0	55	52	119	96	41	8	165
Total Installed Capacity GW	**1094**	**1583**	**848**	**1019**	**1229**	**1812**	**1434**	**1237**	**994**	**2004**
Peak Load (bus-bar) GW	**875**	**1234**	**625**	**718**	**875**	**1234**	**875**	**718**	**625**	**1234**

	RE 39%,Demand3 FY 2047	RE 42%,Demand1 FY 2047	RE 42%,Demand4 FY 2047	RE 44%,Demand2 FY 2047	RE 46%,Demand3 FY 2047	RE 51%,Demand1 FY 2047	RE 54%,Demand2 FY 2047	RE 54%,Demand3 FY 2047	RE 54%,Demand4 FY 2047	RE 62%,Demand4 FY 2047
RE Share by energy	RE 39%	RE 42%	RE 42%	RE 44%	RE 46%	RE 51%	RE 54%	RE 54%	RE 54%	RE 62%
Demand Level	Demand3	Demand1	Demand4	Demand2	Demand3	Demand1	Demand2	Demand3	Demand4	Demand4
Coal	364	578	263	364	364	477	364	364	263	263
Gas_CCGT	50	37	50	50	50	37	50	50	50	50
Nuclear	26	11	26	26	26	11	26	26	26	26
Hydro	75	49	75	75	75	49	75	75	75	75
Biomass+Cogen	8	3	8	8	8	3	8	8	8	8
Hydro_Small	20	20	20	20	20	30	30	30	20	30
Wind	325	325	282	325	325	544	544	544	465	544
Solar	449	921	405	671	824	921	921	921	671	921
Electricity Imports	35	58	70	35	58	70	35	58	70	70
Waste to Electricity	4	6	4	4	4	6	4	4	4	4

Additional Grid Balancing Support	0	210	8	140	0	266	48	0	0	0
Total Installed Capacity GW	1356	2218	1211	1718	1754	2414	2105	2080	1652	1991
Peak Load (bus-bar) GW	**718**	**1234**	**625**	**875**	**718**	**1234**	**875**	**718**	**625**	**625**

In case of several scenarios, significant additional grid balancing capacity would be required primarily to meet the peak demand or to balance the variability in RE generation as seen from Table 9. The following table shows the capacity factors of the additional grid balancing support capacity in each scenario.

Table 12: Capacity factors of the additional grid balancing capacity for each scenario

Scenario	RE Share by energy	Demand Level	Additional Grid Balancing Support (GW) (storage, peaking plants etc)	Capacity Factor %
RE 13%,Demand2 FY 2047	13%	2	24	5%
RE 16%,Demand1 FY 2047	16%	1	75	3%
RE 16%,Demand4 FY 2047	16%	4	0	0%
RE 22%,Demand3 FY 2047	22%	3	55	22%
RE 23%,Demand2 FY 2047	23%	2	52	20%
RE 27%,Demand1 FY 2047	27%	1	119	39%
RE 32%,Demand2 FY 2047	32%	2	96	13%
RE 33%,Demand3 FY 2047	33%	3	41	3%
RE 33%,Demand4 FY 2047	33%	4	8	5%
RE 34%,Demand1 FY 2047	34%	1	165	32%
RE 39%,Demand3 FY 2047	39%	3	0	0%
RE 42%,Demand1 FY 2047	42%	1	210	30%
RE 42%,Demand4 FY 2047	42%	4	8	2%
RE 44%,Demand2 FY 2047	44%	2	140	12%
RE 46%,Demand3 FY 2047	46%	3	0	0%
RE 51%,Demand1 FY 2047	51%	1	266	34%
RE 54%,Demand2 FY 2047	54%	2	48	4%
RE 54%,Demand3 FY 2047	54%	3	0	0%
RE 54%,Demand4 FY 2047	54%	4	0	0%
RE 62%,Demand4 FY 2047	62%	4	0	0%

Note that in case of most scenarios the capacity factors of the additional grid balancing resources is very small indicating that such plants are used only for peaking support, providing ramping services, and balancing the RE variability. For most scenarios with Demand level 1, the planned generation capacity falls short in meeting the demand reliably and the additional capacity is used as an energy resource and not just as a flexibility resource, which is clear from their high capacity factors for example, scenarios RE 51%, Demand 1, or RE27%, Demand 1. For Demand levels 3 and 4 however, very limited balancing capacity is required since the demand is much lower due to enhanced end-use efficiency.

4.2 How is the system operated with high renewable energy penetration?

In this section, we describe the average hourly dispatch for the national grid, which shows how each generation technology contributes towards meeting the demand. The following figure shows the average hourly dispatch for each season in 2047 for the aggressive effort pathway (RE share of 38% by energy by 2047). It can be seen that nuclear and coal power is used as the base load. Hydro is primarily used as a peaking resource but because of the run of the river plants, a large portion also runs as a base load (subject to the water flow constraints). Solar energy does contribute in the peak demand hours (afternoon cooling peak) while nationally, wind energy contributes equally in peak as well as intermediate demand hours.

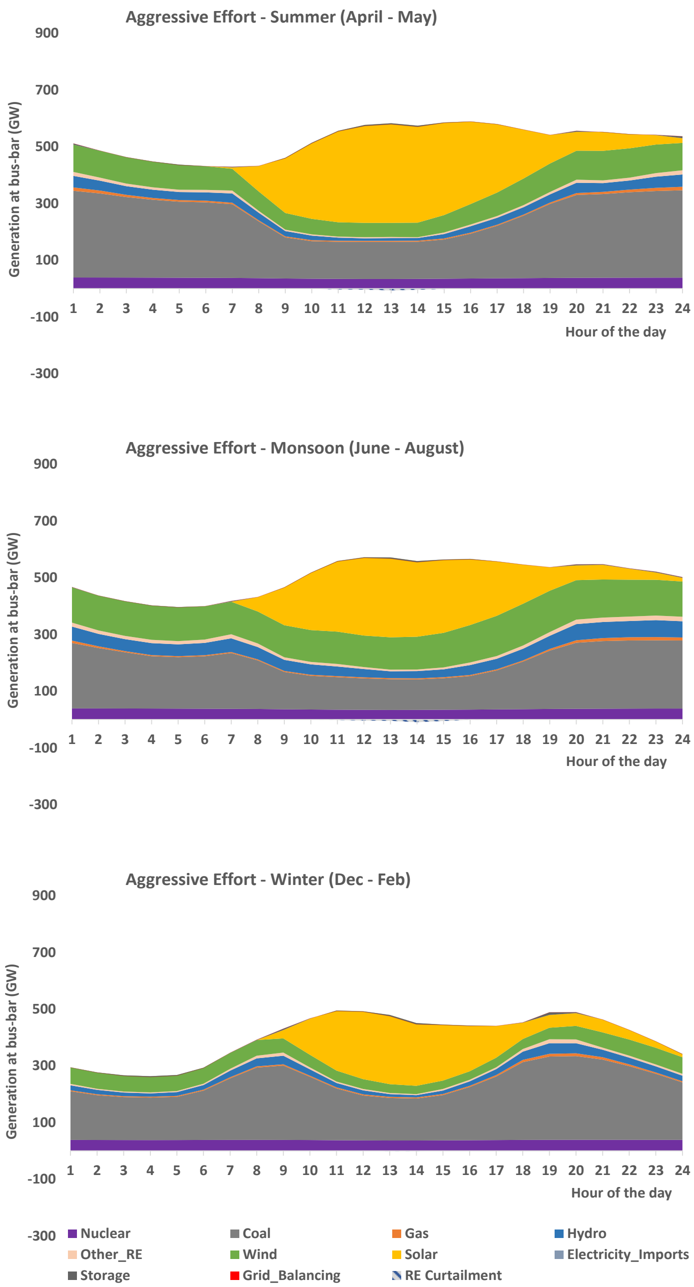
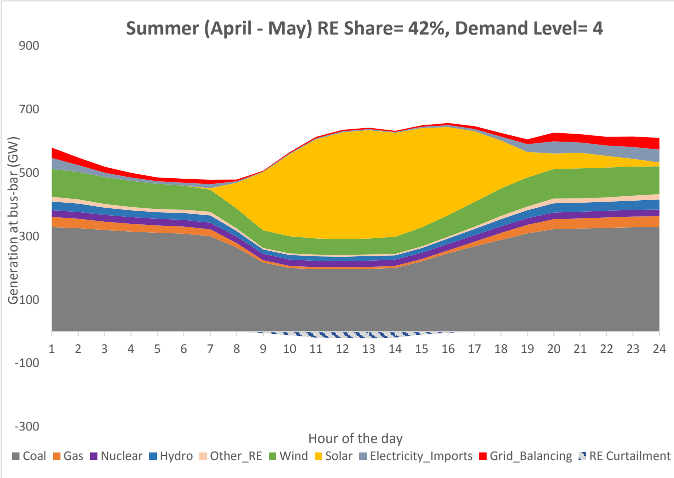


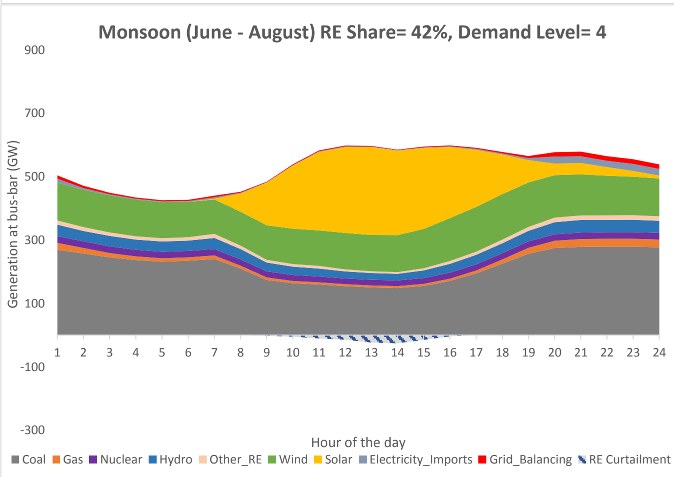
Figure 4: Average hourly dispatch (national) for each season in 2047 in the Aggressive Effort pathway

During summer (April-May) and monsoon (June through September) seasons, renewable energy can provide significant support during afternoon peak demand period during summer (mainly solar) and as well as monsoon (mainly wind). However, in both seasons, gas based generation is necessary to provide the evening ramp-up support and meet the evening peak demand especially after the solar PV generation drops rapidly. Solar CSP (with storage) generation does help in relieving this evening ramp, however its installed capacity is small and thus cannot handle the entire ramp requirement or the evening demand. In Winter, when solar and wind generation both drop, gas / hydro generation provides round the clock energy and load following support despite lower demand. Although Figure 4 shows the dispatch results for the aggressive effort pathway (RE share of 38% by energy), the same trend is observed in all other pathways and scenarios as shown in the annexure.

4.3 When is the flexible capacity dispatched?

Flexible generation capacity is mainly used to meet the evening ramps introduced by the falling solar PV generation, and meeting the evening / night time demand. It is especially important during winter months as wind generation drops to a very low level relative to monsoon; in summer and monsoon, wind generation does provide some support during the evening and night. The following charts shows the average hourly dispatch for all seasons in 2047 in case of the RE 42%, Demand level 4 scenario.





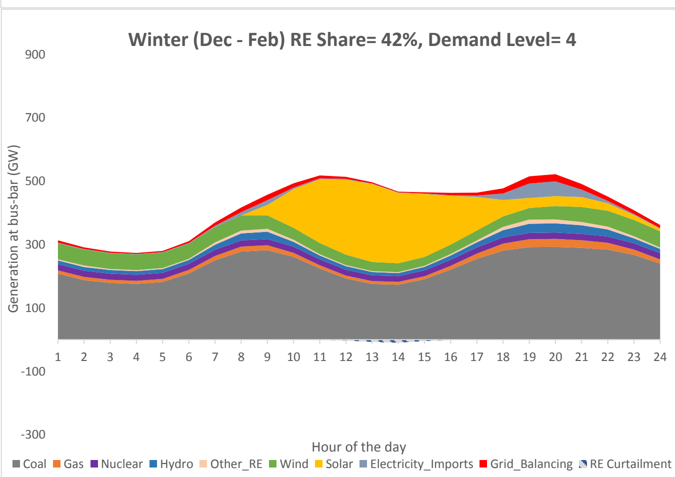


Figure 5: Figure 6: Average hourly dispatch (national) for each season in 2047 in the RE 42%, Demand Level 4 scenario

In the "RE 42%, Demand Level 4" scenario, the flexible capacity planned the IESS is not enough to integrate the renewable energy reliably. Therefore, the model builds additional 20 GW of flexible or grid balancing capacity (assumed to be all gas CT). It could seen from the hourly dispatch charts that the flexible resources including the additional grid balancing capacity should be able to provide cross-seasonal support and its availability of energy in evenings and night especially in winter is crucial for reliable grid service.

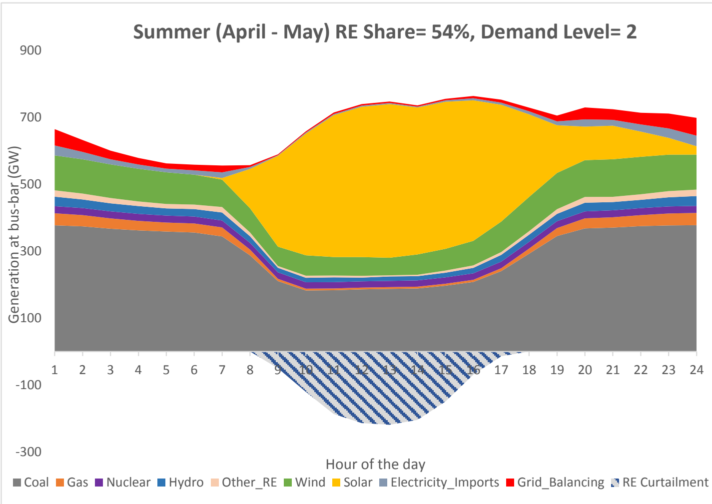
4.4 How much renewable energy could be integrated into the grid?

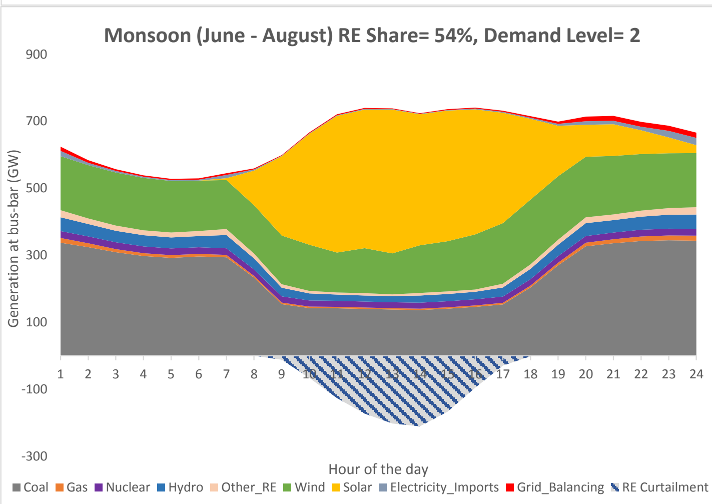
In most of the scenarios considered in this paper, the renewable energy penetration is as high as 30-60% by energy. In some scenarios, the installed capacity of renewables is significantly higher than the system peak demand. For example, in the Heroic Effort or Minimum Emissions pathways, renewable capacity is more than 1400 GW and the system peak demand is 650 GW. Therefore, at times (particularly, during peak RE seasons i.e. summer and monsoon), the total RE generation is more than the demand or the conventional plants cannot back down anymore because of the system security constraints or minimum flow constraints of the hydro power plants. In those hours, renewable energy needs to be curtailed. As shown in the hourly dispatch charts (negative generation), the curtailment could be significant in summer and monsoon (average hourly curtailment reaching as high as ~165GW in monsoon). For Heroic effort and Minimum Emissions pathways, more than 15% of the energy generated by wind and solar projects needs to be curtailed for a reliable grid operation, which is as high as 80% of the total hydro generation.

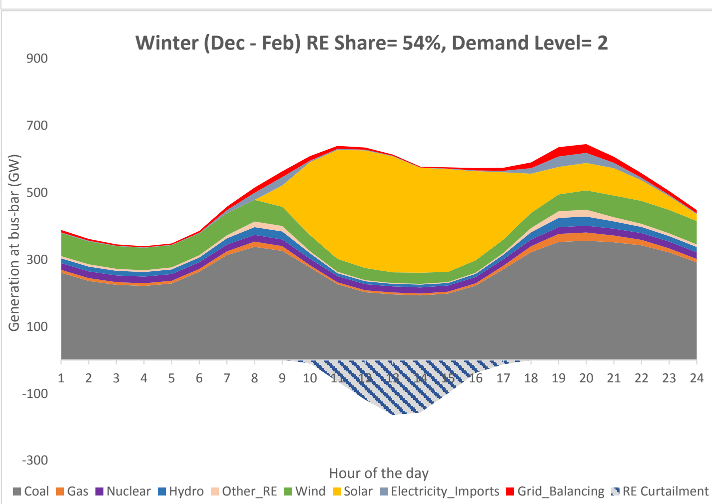
The following table shows the RE curtailment in the selected scenarios.

Pathway	Renewable Energy Curtailment (as % of RE generation)
Least Effort	0%
Determined Effort	0%
Aggressive Effort	4%
Heroic Effort	32%
Renewable and Clean Energy	20%
Pathway X	0%
Min Emissions	24%
Max Energy Security	21%
RE 13%,Demand2 FY 2047	0%
RE 16%,Demand1 FY 2047	0%
RE 16%,Demand4 FY 2047	0%
RE 22%,Demand3 FY 2047	0%
RE 23%,Demand2 FY 2047	0%
RE 27%,Demand1 FY 2047	0%
RE 32%,Demand2 FY 2047	0%
RE 33%,Demand3 FY 2047	1%
RE 33%,Demand4 FY 2047	0%
RE 34%,Demand1 FY 2047	0%
RE 39%,Demand3 FY 2047	2%
RE 42%,Demand1 FY 2047	1%
RE 42%,Demand4 FY 2047	2%
RE 44%,Demand2 FY 2047	2%
RE 46%,Demand3 FY 2047	21%
RE 51%,Demand1 FY 2047	1%
RE 54%,Demand2 FY 2047	13%
RE 54%,Demand3 FY 2047	21%
RE 54%,Demand4 FY 2047	15%
RE 62%,Demand4 FY 2047	28%

The following chart shows the average hourly dispatch for RE54%, Demand Level 2 scenario and clearly shows the RE curtailment (plotted as the blue striped area with negative generation value).







Significant increase in the RE capacity requires the conventional plants to back down to their minimum; when conventional generators cannot back down any further, RE curtailment becomes necessary. It can be seen from the dispatch charts that RE curtailment is the highest during summer and monsoon; the curtailment reduces significantly in winter primarily because of the steep reduction in wind generation. Curtailment typically peaks between 11 AM to 2 PM (which is solar PV peak generation period). But there is still need for additional flexible capacity to meet the evening / night demand. This has an important implication for the storage options. The cost effective storage solution should be able to transfer the energy from summer/monsoon to winter i.e. offer cross-seasonal support; also, on the daily basis, it should be able to store the curtailed renewable energy in the late morning / early afternoon and deliver it in the evening / night.

5 Discussion and Conclusion: Key long term investment options for enhancing system flexibility in India

In this analysis, we have assessed the technical feasibility of a range of aggressive renewable energy penetration scenarios for 2047 as defined in the NITI Aayog's India Energy Security Scenarios model. We estimate the flexible generation capacity requirement for integrating the aggressive renewable energy targets reliably and simulate hourly operation of the electricity grid (national level) using PLEXOS, a widely used grid dispatch simulation software. We project hourly national demand in 2047 using the historical hourly demand patterns adjusting for rapid urbanization and changing usage patterns. We use actual hourly generation and solar irradiance (DNI and GHI) data to project the hourly wind and solar generation profile for 2047. We develop assumptions regarding operation and performance of generation technologies based on the historical actual data, and fuel prices based on long term historical trends.

We find that in all the twenty seven scenarios we considered, all with a varying degree of RE penetration, grid integration is technically feasible. However, in certain scenarios, the flexible generation capacity is not found to be enough for reliable grid integration; we estimate such additional flexible capacity required. In general, during summer (April-May) and monsoon (June through September) seasons, renewable energy can provide significant support during afternoon peak demand period; solar PVs in summer and wind in monsoon. However, in both seasons, flexible generation capacity is necessary to provide the evening ramp-up support and meet the evening peak demand especially after the solar generation drops rapidly. In Winter, when solar and wind generation both drop, gas based generation provides round the clock energy and load following support despite lower demand.

The regional diversity in renewable energy generation in India and its complementarity with demand as well as other RE resources help reducing the impact of extreme events such as sudden loss of RE generation or over-generation, etc. on the system. In this analysis, we have assumed future capacity addition in the renewable energy resources happens on the same sites as the current installed capacity. This is a highly conservative assumption for diversity and hence will significantly overestimate the variability in RE generation. Despite this, we found that the system can handle extreme events in RE generation – low and high generation and high variability. However, in a few scenarios especially the ones with higher than 35-40% renewable energy penetration, significant RE curtailment (about 10-20% of the RE generation) is found to be necessary.

Note that an implicit assumption in this analysis is the ability to perfectly forecast renewable energy generation on a day-ahead basis; RE forecasting is absolutely crucial for reliable grid integration. With newer state-of-the-art forecasting techniques, forecast errors have been reducing rapidly especially with the use of the real-time generation data. With installation of Renewable Energy Management Centers and the new forecasting regulations for the interstate RE generators, India has already started creating a robust framework for RE forecasting.

One of the key attributes of the flexible capacity for RE integration in India are found to be (a) cross-seasonal support, and (b) availability of energy in evenings and night especially in winter. This has an important bearing on the choice of the flexible resources in the long term. Below, we describe some of the key possible options (in the medium to long term) for adding flexibility to the system.

5.1 Onsite gas storage and open cycle operation of CCGT plants

India has acute gas shortages. None of the gas-based power plants have a gas storage facility onsite or anywhere upstream; therefore, all gas-based plants are dependent on the gas availability in the pipeline or LNG supply and availability of the regasification facility. As a result, their availability for providing ramping support is limited. Moreover, currently, all CCGT plants are required to operate in a combined cycle model; their gas turbine cannot operate in the open cycle mode. Therefore, if the current practices continue even in the future, CCGT gas may not be a fully viable option for providing this flexible grid support unless they can operate in an open cycle mode. Also, in order to deal with the lack of gas availability in India, if gas plants have onsite gas storage, their efficacy as a flexible resource would increase significantly and the need for additional flexible resources may reduce. Other solution is building more gas power plants on the shore based on imported LNG – however, such approach may involve significant price and supply risks.

5.2 Incentivizing hydro plants for participation in the ancillary services and real time markets

A large part of India's hydro capacity is run-of-river. Also, many reservoir plants are multi-purpose and have to match their generation schedule with the water release schedule for irrigation, drinking, and industrial use. Therefore, hydro, although capable of ramping very fast, may not be able to provide the ramping support commensurate with its potential. The role of real time or ancillary services markets is therefore crucial for incentivizing the changes that may be necessary in the current power system operations practices.

5.3 Flexible thermal generation

Conventional thermal power plants (coal based) are typically not considered a flexible resource. However, super-critical and ultra-super critical coal power plants can ramp at a much faster rate than the subcritical plants mainly due to higher temperature in the boiler. Secondly, the minimum generation level of coal power plants is specified to be 55% of the installed capacity currently while the standard practice is not going below 70% of the installed capacity. If the coal power plants can ramp faster and can operate at much lower minimum generation levels, the need for additional balancing resources and (thus total RE integration costs) would reduce significantly.

5.4 Storage

Note that with aggressive RE penetration, winter requires significant energy support especially to meet the evening and night demand. This implies that the cost-effective energy storage solution should be cross-seasonal i.e. it should be able to transfer the energy from summer/monsoon to winter. Also, on a diurnal basis, it should be able to store the energy in the late morning / early afternoon (when RE curtailment peaks) and delver in the evening / night. Battery storage or other diurnal storage technologies would help manage the diurnal capacity support issues (like ramping, reserves, and other ancillary services) in summer or monsoon, but their support would be limited for cross-seasonal applications. Hydro projects (with optimized dispatch) could serve as a viable option for cross-seasonal energy storage; however, their effectiveness would be restricted given the long construction lead times and limited potential in the country. Therefore, aggressive demand response (for peak capacity issues) and energy efficiency programs (for energy support) would be the key to the grid balancing solutions.

5.5 Transmission and markets

One of the most cost effective ways to introduce flexibility in the system is creating appropriate markets for flexible products (such as real time energy, ancillary services etc.) and ensuring liquidity in the market. India already has a 24x7 day-ahead market, while in 2016 it has also introduced a framework for the ancillary services market. Although India does not have a formal real time market, the deviations from the day-ahead schedule are settled using a frequency dependent price. In any market, strengthening the transmission network by eliminating the key bottlenecks is key to enhancing liquidity. Our previous analysis of RE grid integration in India for 2022 suggests that the current inter-regional transmission flows in India would significantly change with growing RE penetration. For example, since majority of the wind energy potential in India is concentrated in the south and west, power from the southern and western regions may need to flow to northern and eastern regions; this is exactly opposite of the current power flow. Moreover, given the diurnal variations in the solar and wind generation, there are reversals of the net flow on the inter-regional interfaces in a span of one day (Phadke, Abhyankar, and Deshmukh 2016). A robust regulatory and market framework is a must for such free flow of power.

Given the ambitious targets of renewable energy in the country, such studies that assess the impact of large scale integration of RE as well as discussions on the potential policy, regulatory, and institutional framework are crucial. This study serves as one of the first few of our forthcoming series on RE grid integration in India. However, note that this analysis is based on significant simplifications and assumptions especially regarding the transmission system and the deviation settlement mechanism. Therefore, the results and conclusions presented in the paper, especially about the generation and transmission system investments should be viewed only as high-level indications of the impacts of the aggressive penetration of renewable energy on the Indian grid. Significant refinement to this analysis would be necessary for actual power system planning purposes.

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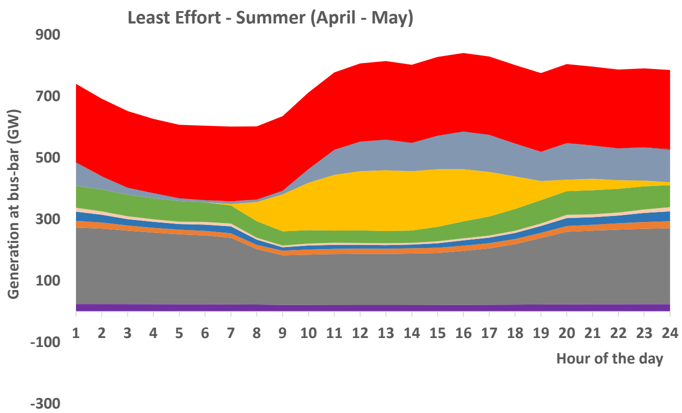
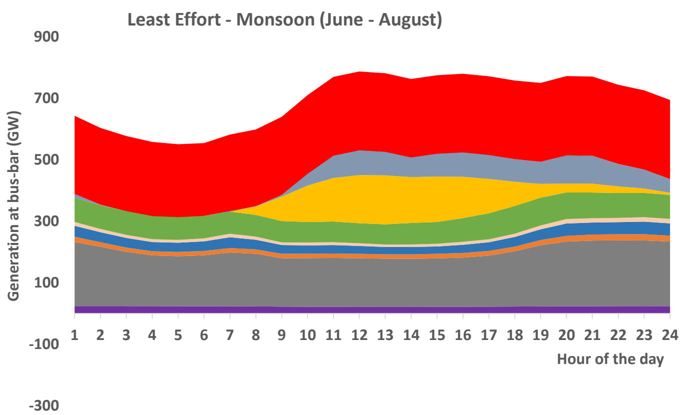
Annexure: Average Hourly Dispatch for Key Pathways and Scenarios

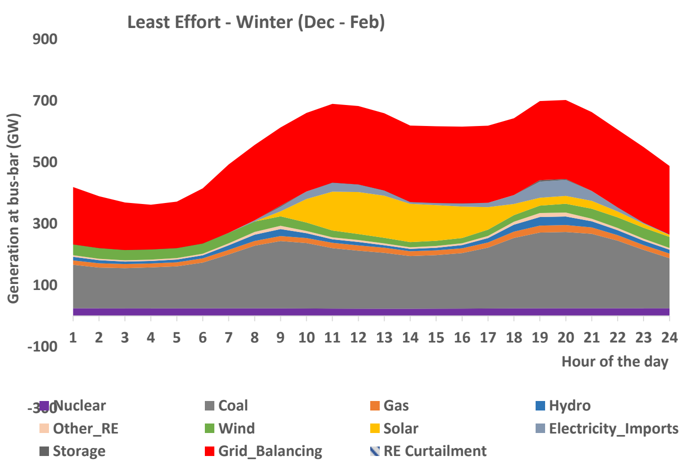
Least Effort Pathway

Key insight: Electricity Imports (from the Calculator) and Grid Balancing resources dominate the total supply. Although renewables penetration is significantly lower than the other pathways, significant grid balancing support is required – mainly as a base load energy resource.

Average hourly dispatch in each season



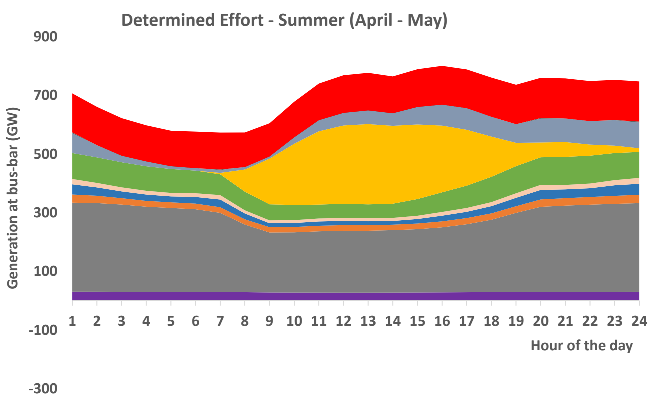


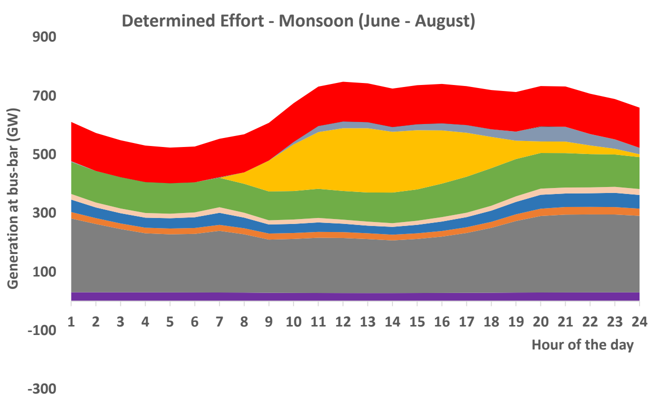


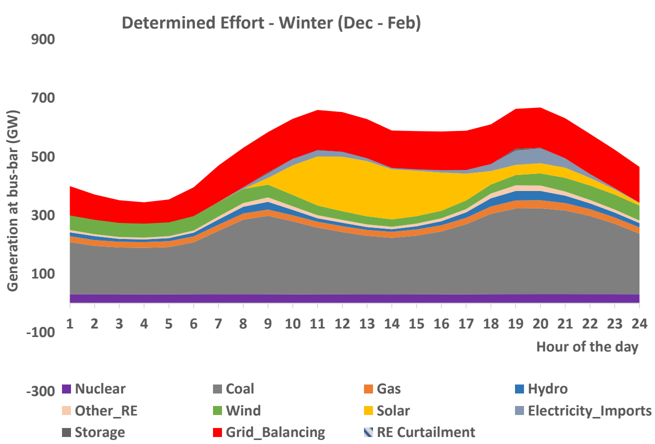
Determined Effort Pathway

Key insight: Solar PV and CSP (with thermal storage) make significant dent in the summer afternoon peak, while wind provides significant electricity in monsoon. However, grid still needs additional balancing resources as a base load supply to meet the demand; solar thermal storage does help, but given its installed capacity the grid needs additional balancing support.

Average hourly dispatch in each season



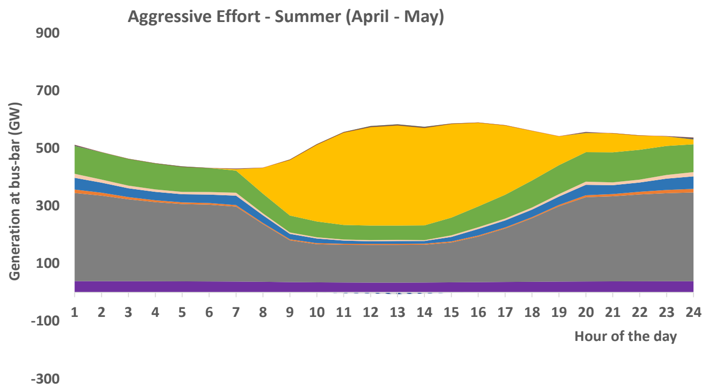


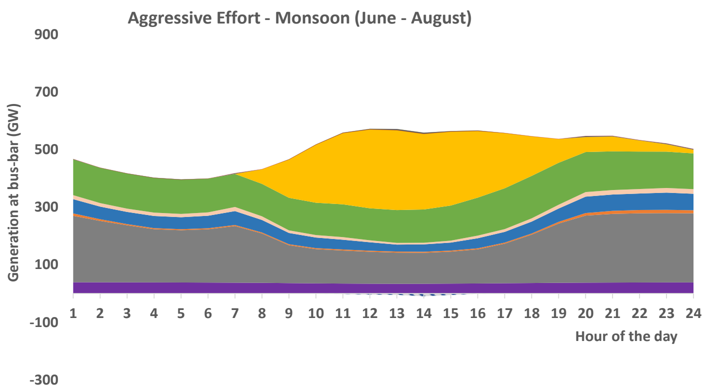


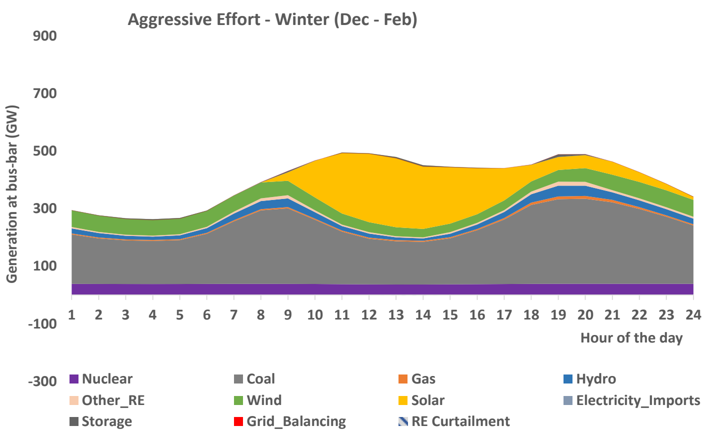
Aggressive Effort Pathway

Key insight: Renewable energy generation increases. But there is enough conventional capacity in the grid to integrate that. No RE curtailment is necessary.

Average hourly dispatch in each season



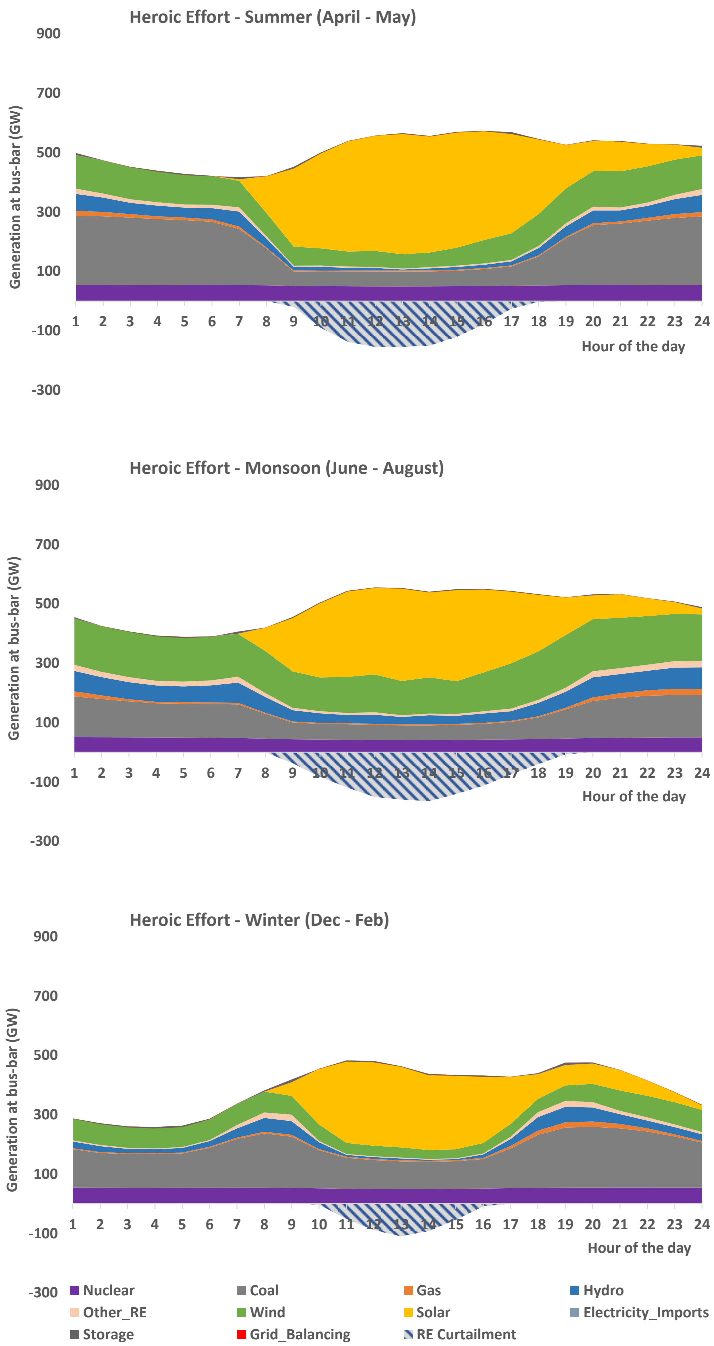




Heroic Effort Pathway

Key insight: Significant increase in the RE capacity requires the conventional plants to back down to their minimum during summer and winter. Given the large conventional capacity available, no additional grid balancing is required but significant RE curtailment is necessary in all seasons. Solar CSP (with storage) helps in meeting the evening peak demand in all seasons.

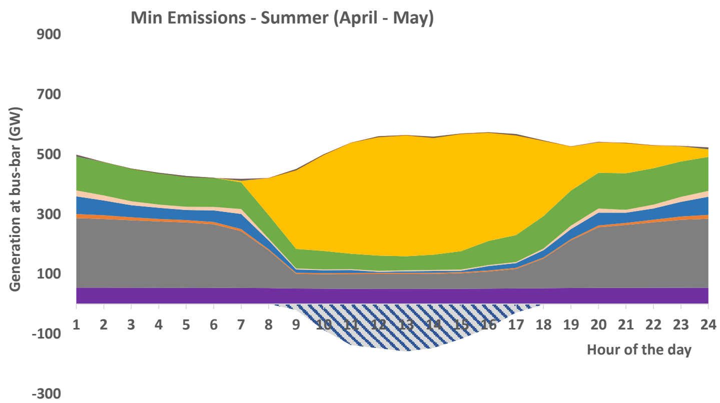
Average hourly dispatch in each season

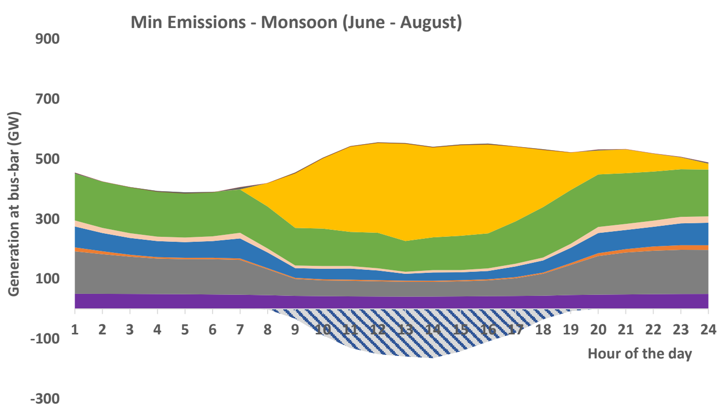


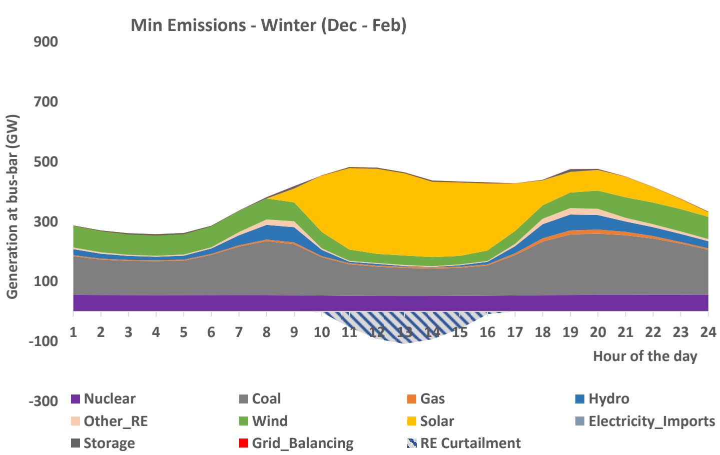
Minimum Emissions Pathway

Key insight: Significant increase in the RE capacity requires the conventional plants to back down to their minimum during summer and winter. Given the large conventional capacity available, no additional grid balancing is required but significant RE curtailment is necessary in all seasons. Solar CSP (with storage) helps in meeting the evening peak demand in all seasons.

Average hourly dispatch in each season



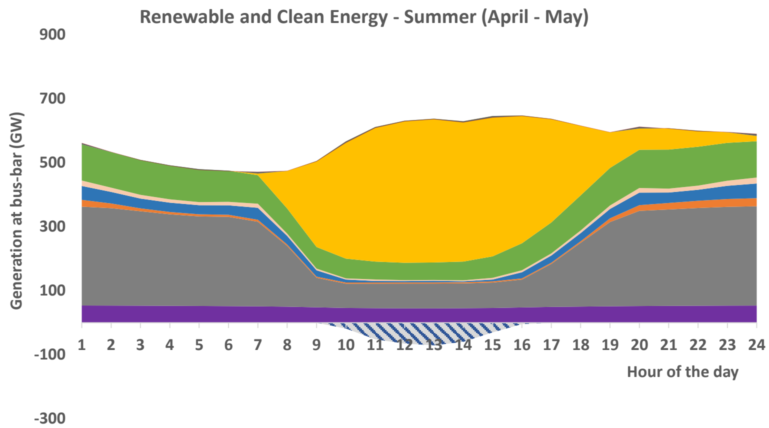


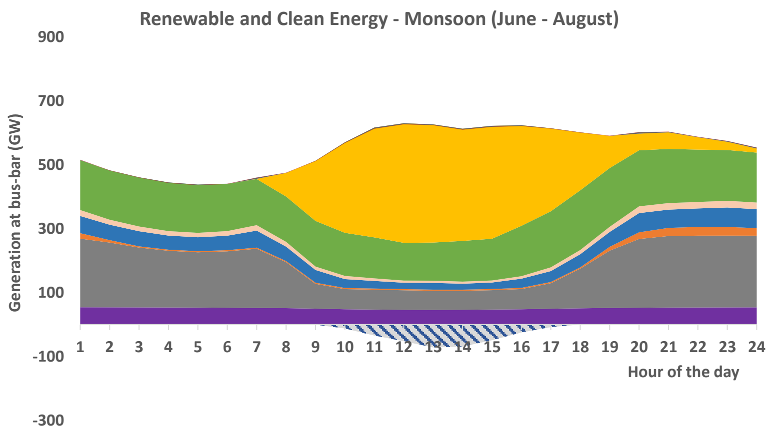


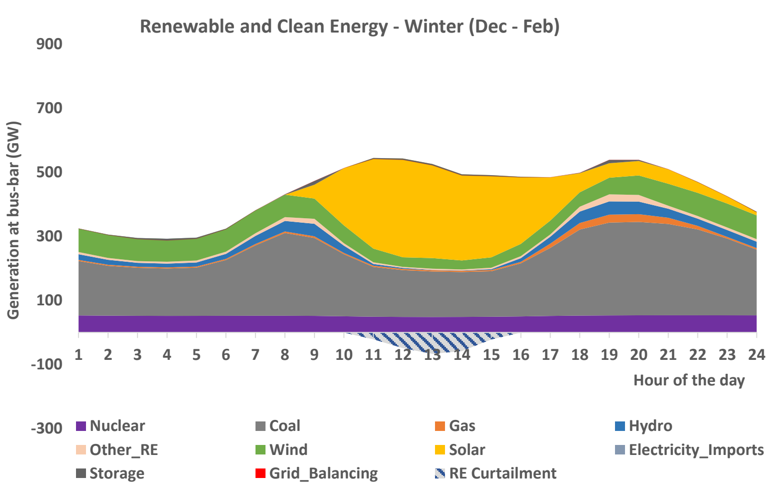
Renewable and Clean Energy Pathway

Key insight: RE penetration is lower than the Minimum Emissions and Heroic Efforts Pathways. Therefore, RE curtailment is significantly lower (~5%). The grid still has very large under-used conventional capacity. Therefore, no additional balancing support is required.

Average hourly dispatch in each season



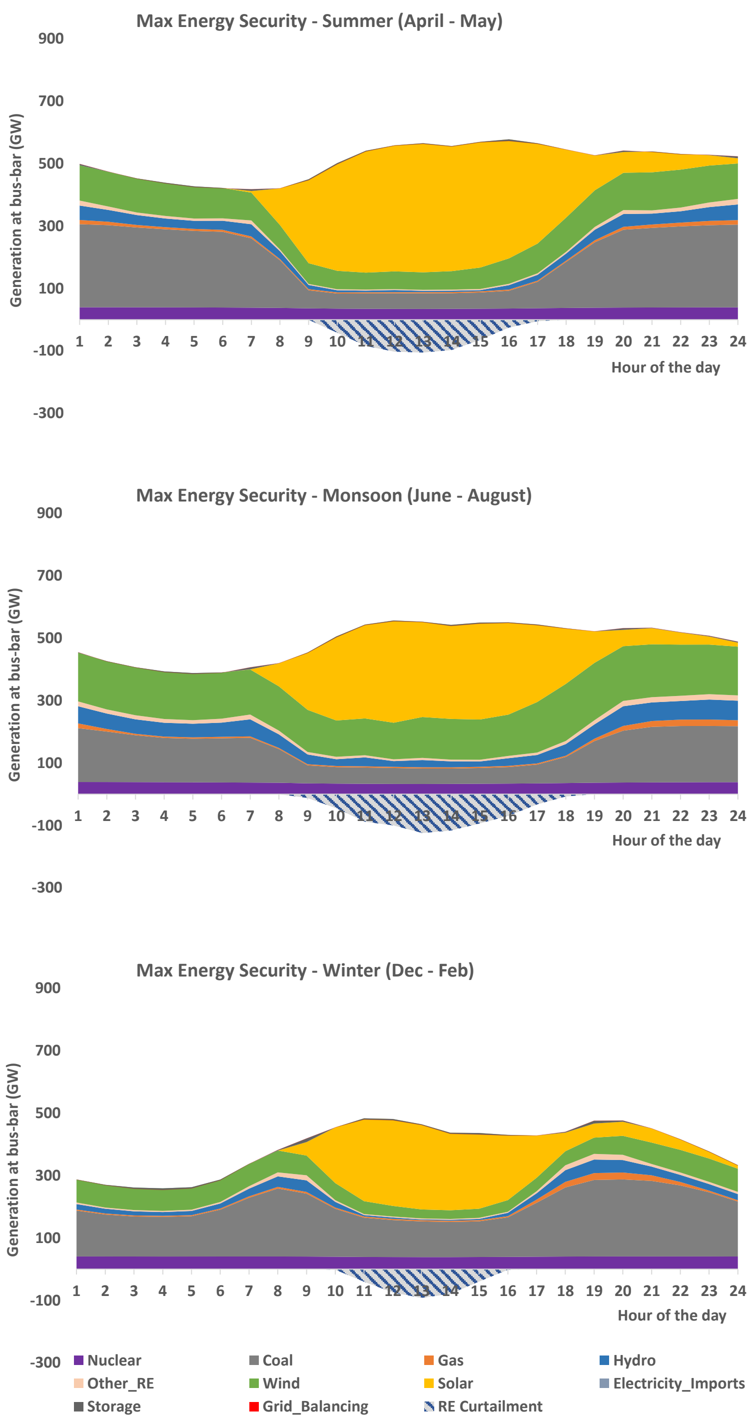




Maximum Energy Security Pathway

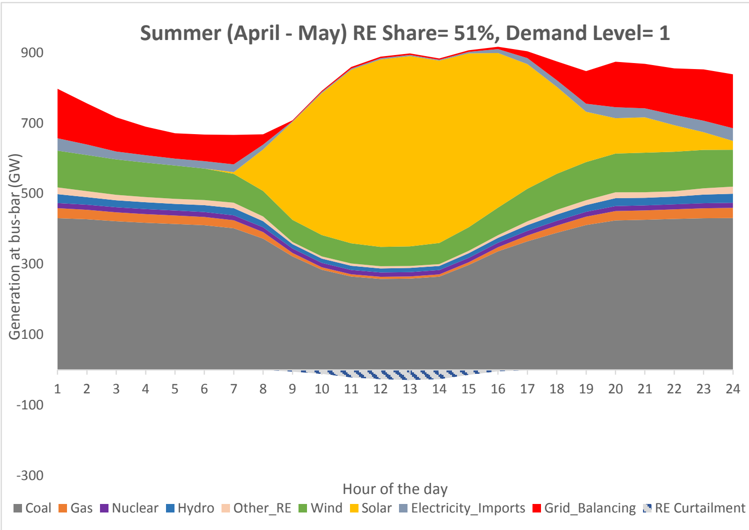
Key insight: RE penetration is lower than the Minimum Emissions and Heroic Efforts Pathways. Therefore, RE curtailment is somewhat lower. The grid still has very large under-used conventional capacity. Therefore, no additional balancing support is required.

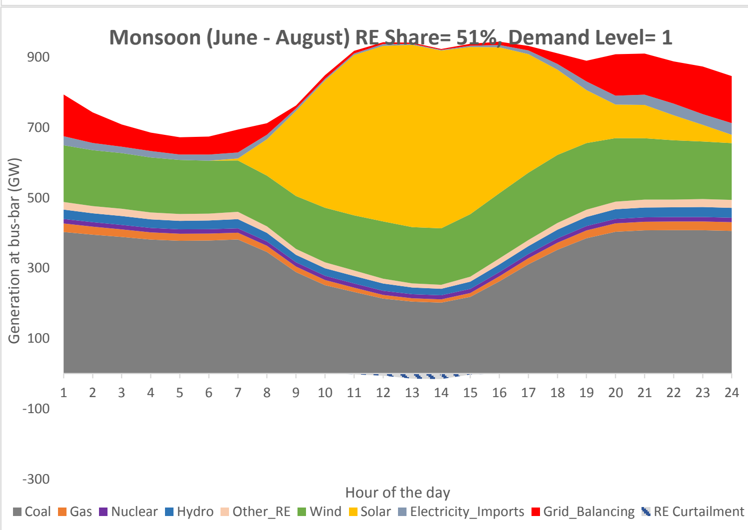
Average hourly dispatch in each season

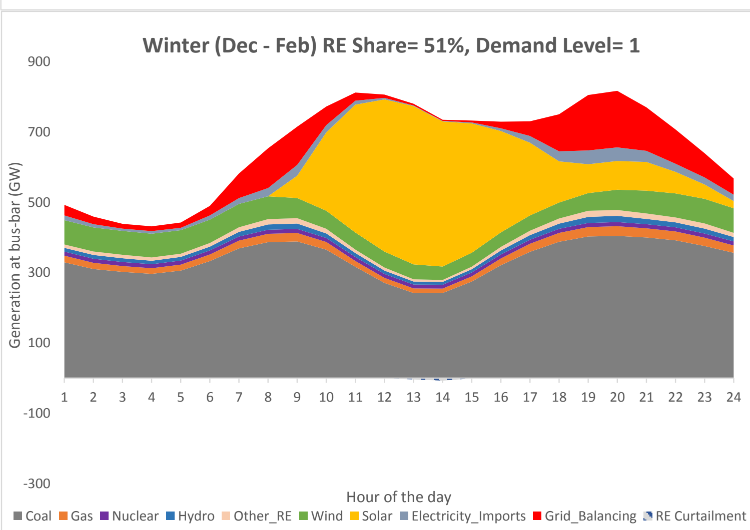


Scenario: RE Share 51%, Demand Level 1:

Grid balancing capacity is used in the night after solar generation drops. But no RE curtailment is necessary.

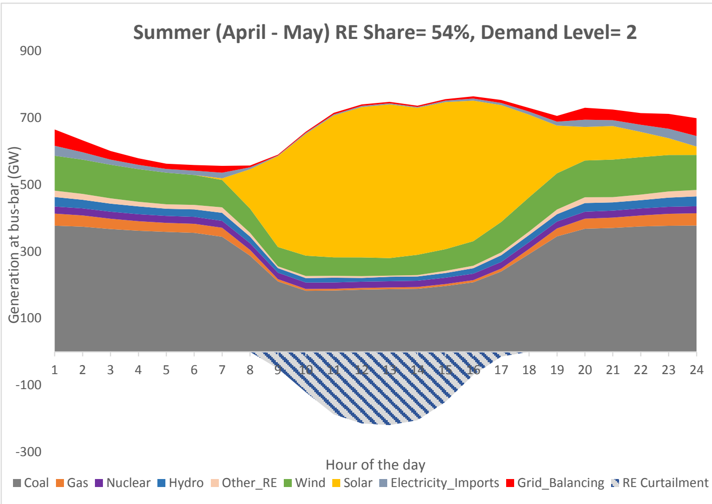


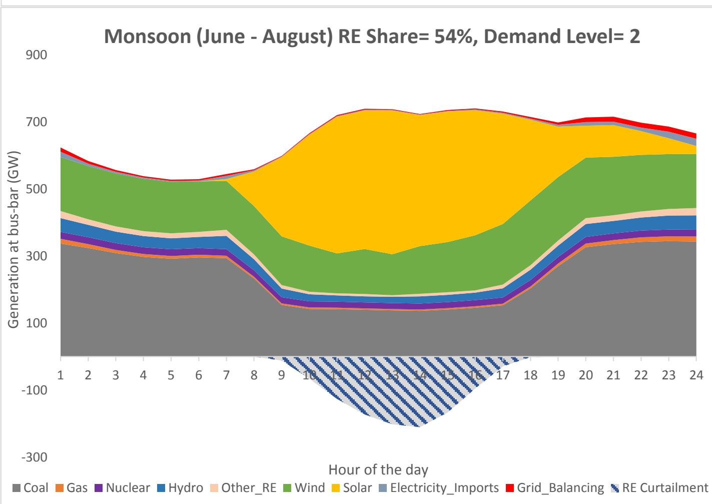


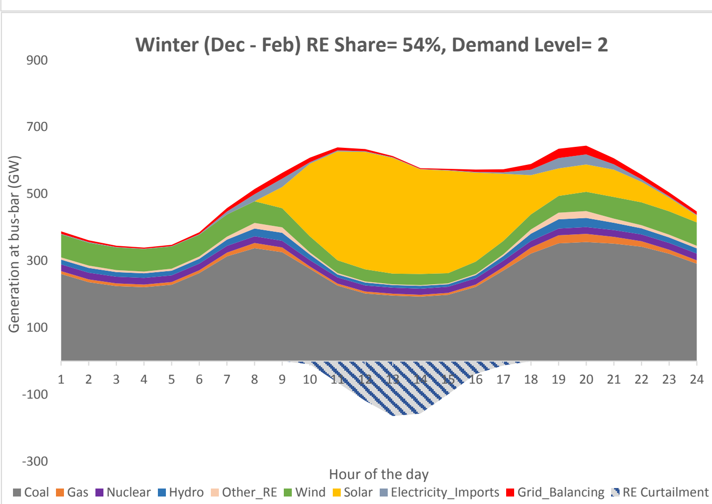


Scenario: RE Share 54%, Demand Level 2:

Grid balancing capacity is used in the evening and night to the meet the load and system ramping requirement after solar generation drops. Significant RE curtailment is necessary.

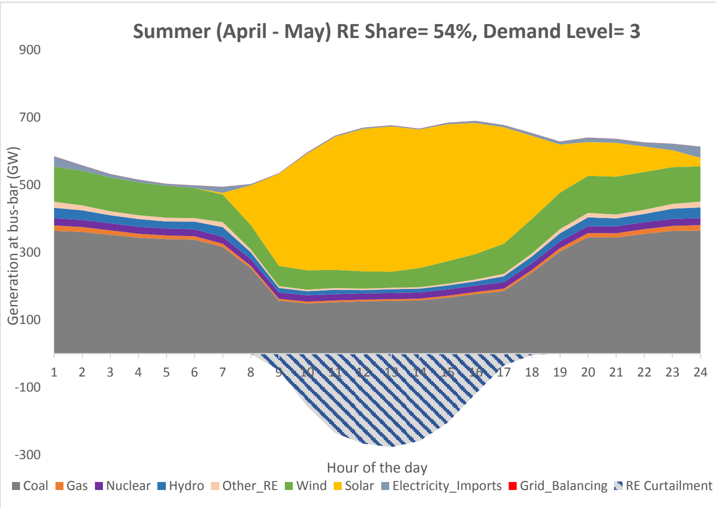


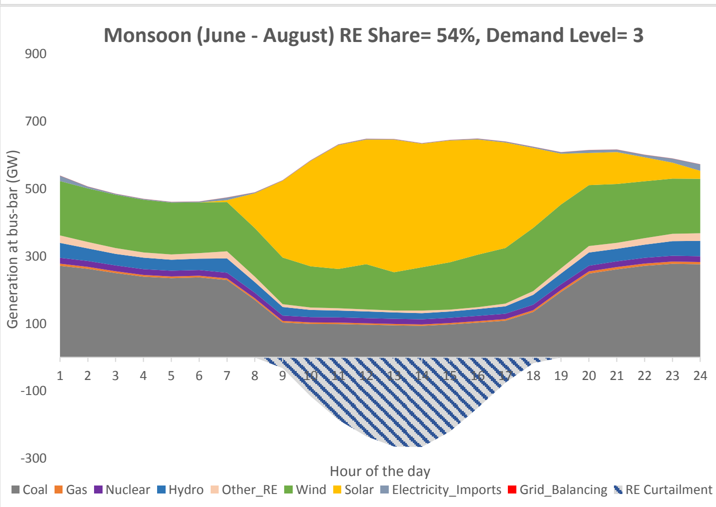


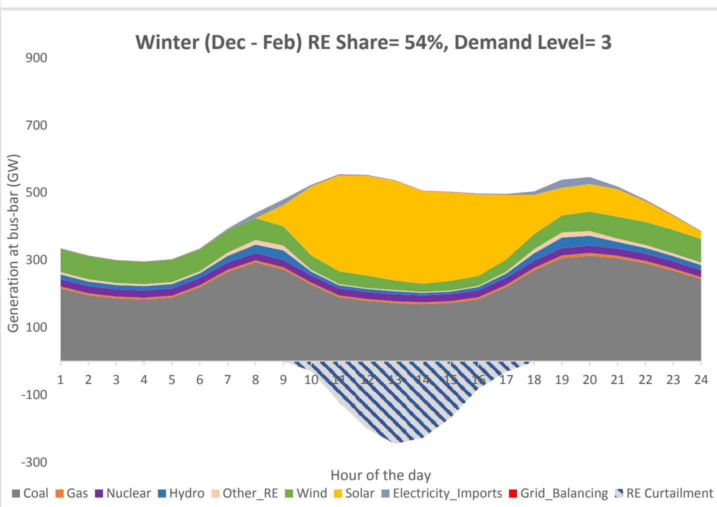


Scenario: RE Share 54%, Demand Level 3:

Grid balancing capacity is not required primarily because of over-capacity in conventional generation. Significant RE curtailment (mostly solar curtailment) is necessary.







Scenario: RE Share 42%, Demand Level 4:

Small amount of grid balancing capacity is required primarily to meet the evening and night load and system ramping requirement after solar generation drops. Also, RE curtailment is very low.